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THE INSTITUTION OF PETROLEUM TECHNOLOGISTS.

THE ONE HUNDRED AND FIFTY-SEVENTH GENERAL MEETING of the Institution of Petroleum Technologists was held at the House of the Royal Society of Arts, John Street, Adelphi, London, on Tuesday, April 10th, 1934, Mr. T. DEWHURST (President) in the Chair.

The Secretary read the names of candidates nominated for election, and the following list of members elected :—

As Members.—Clifford Banta, Theodore Cohn, Georges Godeau, Leonid Nakhimoff, Leonard Patrick.
As Transfer to Member.—Eustace T. Vachell.
As Associate Member.—Schofield Labrow.
As Transfer to Associate Member.—Harold Wilfred Hastings.
As Associates.—Frank Dakin, Walter George Dale.

The following paper was presented by the author :—

The Surveying of Deep Boreholes, with Special Reference to some work recently performed in Burma with the Martienssen Equipment.

By Capt. W. E. BRUGES, M.Sc., A.C.G.I., D.I.C., Assoc. M.Inst.C.E. (Associate).

I.

THE surveys referred to in the following paper were recently performed in Upper Burma, with apparatus designed and manufactured by Professor Martienssen. Comments are made on the surveying of oil wells generally, and in particular on the results obtained with this equipment.

The survey of a borehole usually consists of measuring its inclination to the vertical directionally at various predetermined points throughout its length. Thence, the deviation is calculated and a plan view of the hole is drawn. Such a plan view appears as in Fig. 1, which is the result of a survey of an oil well to a depth of 3000 ft., the inclination having been measured every 164 ft. (50 metres).

Although a great deal of thought has been given to the subject, and many different types of well-surveying apparatus have been invented, the practice of surveying oil wells has by no means been universally adopted. It is not generally realised that, owing to the peculiar difficulties, which will be explained, accurate and exact oil-well surveying is quite a difficult engineering proposition. In consequence of this, surveys are often attempted with inadequate apparatus. Some of the results so obtained are positively deceptive, and very little useful information can be deduced from any of them. Such surveys are often assumed to be correct when no other method

is available, and, as a result, well-surveys generally are commonly regarded as not being worth a great deal of expense. This is unfortunate, for really accurate surveys of oil wells should provide a source of information and an invaluable reference to be studied in conjunction with the drilling logs and geological data. Before the Martienssen apparatus was taken to Burma, some of the difficulties were made specially apparent when a survey of an oil well in Germany was attempted with it. Subsequent experiments in Burma showed it to be one of the most satisfactory existing apparatus for well-surveying.

Surveys of oil wells are useful to the drillers, geologists and to the management of an oil company. As far as the geologists are concerned, the uses are mainly for :—

Correction of underground contour maps.

Choosing correct locations above ground, so that wells will be spaced properly in an oilsand.

Making deductions as regards the formation from the direction and amount of deviation, and from irregularities in the course of the hole.

It is very important that the spacing of wells in an oilsand should be known to the management of a company. Particularly is this the case if production has decreased considerably for no known reason, and it is thought likely that a number of holes are running very close to one another. The drilling has to be checked ; and here again a survey is useful.

Legal questions may also arise. A great objection to well-surveying in the past has been that one company's well may be found to be deviating under another company's territory. Also, a number of surveys may show a general tendency for deviation in a particular direction, so that other unsurveyed wells near a boundary may be shown to be likely to be deviating into another's territory. Surveys may in the future be ordered by Governments, particularly in countries where they are interested in production owing to the large royalties which they take from the oil. This applies particularly to Burma, where the taxation has been described by a well-known Company as "punitive." Oil companies might, it is suggested, persuade the Government to supply the surveying apparatus and to perform surveys without charge for all companies, on the ground that the extra yield due to improved spacing of the oil wells would repay its cost.

A knowledge that their work was going to be checked, should act as an incentive to efficiency on the part of the drillers. Accurate surveys should also enable them to check the effect of their methods of drilling, and of different drilling operations. Sometimes it is thought advisable to keep surveys as confidential information ; and

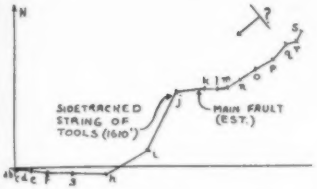


FIG. 1.

HOLE A. DRILLED WITH ROTARY TOOLS TO 1610 FT. (J) AND COMPLETED WITH CABLE TOOLS.

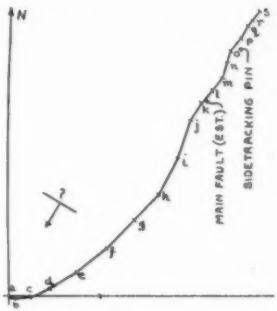


FIG. 2.

HOLE B. DRILLED WITH ROTARY EQUIPMENT.

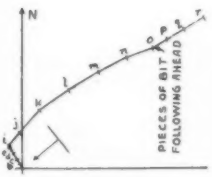


FIG. 3.

HOLE C. DRILLED BY CABLE TO 1375 FT. (H/I); THEN, AFTER A LONG INTERVAL, CONTINUED BY ROTARY.

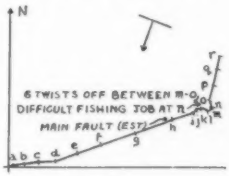


FIG. 4.

HOLE E. DRILLED WITH ROTARY EQUIPMENT.

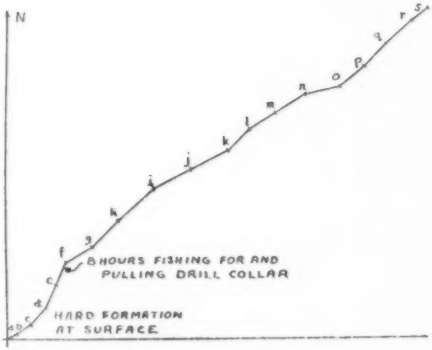


FIG. 5.

HOLE F. DRILLED WITH ROTARY EQUIPMENT.

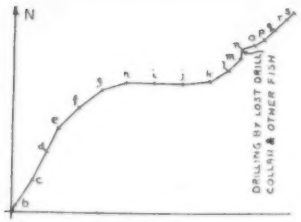


FIG. 6.
HOLE H. DRILLED WITH ROTARY EQUIPMENT.

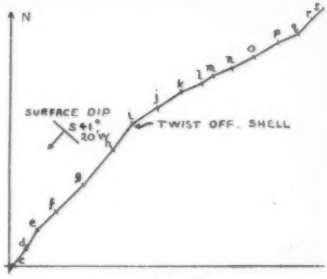


FIG. 7.
HOLE J. DRILLED WITH ROTARY EQUIPMENT.

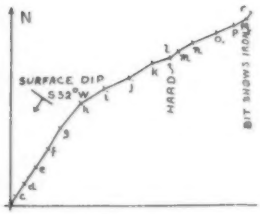


FIG. 8.
HOLE K. DRILLED WITH ROTARY EQUIPMENT.

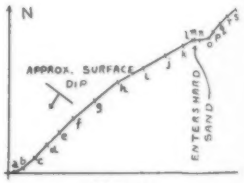


FIG. 9.
HOLE L. DRILLED WITH ROTARY EQUIPMENT.

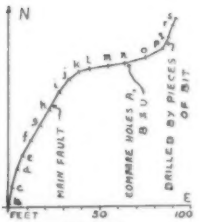


FIG. 10.
HOLE M. DRILLED TO 1700 FT. (J/K) WITH CABLE AND COMPLETED WITH ROTARY EQUIPMENT.

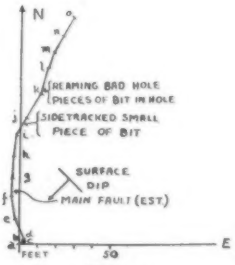


FIG. 11.
HOLE P. DRILLED TO 220 FT. WITH CABLE TOOLS AND COMPLETED WITH ROTARY (DEVIATION OF FIRST 220 FT. (A–B) VERY SMALL) IN A WESTERLY DIRECTION.

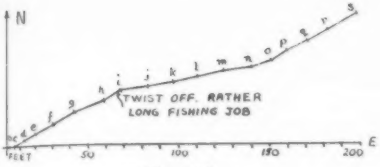


FIG. 12.

HOLE Q. DRILLED WITH CABLE TOOLS TO 306 FT. (B) AND COMPLETED WITH ROTARY.

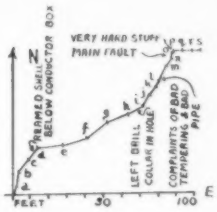


FIG. 13.

HOLE T. DRILLED WITH ROTARY EQUIPMENT.

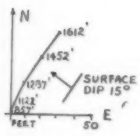


FIG. 14.

HOLE W. DRILLED WITH CABLE TOOLS.

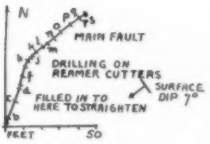


FIG. 15.

HOLE Y. DRILLED WITH CABLE TOOLS.

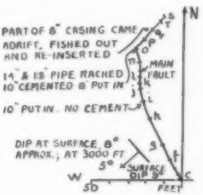


FIG. 16.

HOLE Z. DRILLED WITH CABLE TOOLS.

FIGS. 1-16.

SCALE OF DEPTH.

a–b, b–c, etc. = 50 metres = 164 ft.

	Metres.	Ft.		Metres.	Ft.
Floor to a	50	164	Floor to k	550	1804
" " b	100	328	" " l	600	1968
" " c	150	492	" " m	650	2132
" " d	200	656	" " n	700	2296
" " e	250	820	" " o	750	2460
" " f	300	984	" " p	800	2624
" " g	350	1148	" " q	850	2788
" " h	400	1312	" " r	900	2952
" " i	450	1476	" " s	950	3116
" j	500	1640			

they are not shown to the drillers concerned, on the ground that straightening out can be accomplished without a knowledge of the direction in which the hole is deviating—usually by a process of slow drilling. However, a knowledge of surveys, besides increasing the efficiency of the driller, should tend to give him more confidence and an ability to avoid trouble arising from the local conditions and tendencies, which the surveys would show up. Surveys of nearby wells, as well as that of the well being drilled, should be provided. For this purpose, the value of the surveys increases with their accuracy.

As regards the geologists, we have first to consider the correction of underground contour maps. Sometimes it is necessary to correct these with great accuracy; a knowledge of whether a well passes through a fault above or below an oilsand may be desired. More often, however, great accuracy is neither possible nor necessary, and a rough knowledge of the underground structure is all that is required. Improvements in drilling machinery and methods have much reduced the inclinations of oil wells. Inclinations of not greater than two degrees in wells 3000 ft. deep are common; so that in a great many cases verticality can be assumed in calculating the point at which the well penetrated a particular horizon. In most cases, approximate surveys would be sufficient for this purpose.

Again, for spacing wells in a producing oilsand, surveys of great accuracy would not as a rule be necessary; the need of accuracy increases with the depth of the well. A time comes when a geologist has to decide whether or not an oil field should be abandoned, and it is impossible to come to a satisfactory decision without a knowledge of the spacing of the wells in the producing sands.

In connection with the making of deductions as to the formation from the direction and amount of deviation and from the irregularities in the course of a hole, a number of charts (Figs. 1–16) are exhibited. The amount and the direction of the dip of the strata are likely to affect the amount and direction of deviation, so that well-surveys may provide the geologists with information in this manner. Figs. 17 and 18 show the relative positions of a number of oil wells. These are deviating generally in an up-dip direction. The form lines on Fig. 18 are such as might be deduced from the deviations of the wells and from surface indications. They are drawn to illustrate remarks which follow and which deal with mechanical effects which a particular formation might have on the direction and amount of deviation. Fig. 17 is an abridgment of a geological map drawn by Mr. Mainprise, and is given as correct.

It will be shown that there are mechanical reasons why cable wells in strongly marked strata should tend to deviate in an up-dip

direction when the dip is less than some critical angle. In the examples given, this angle is estimated to be about 7°. Examples are Figs. 15 and 16.

When the dip is over about 11° and less than another higher critical angle, cable holes seem to deviate in a strike direction; generally to the left of one facing up-dip (Fig. 14).

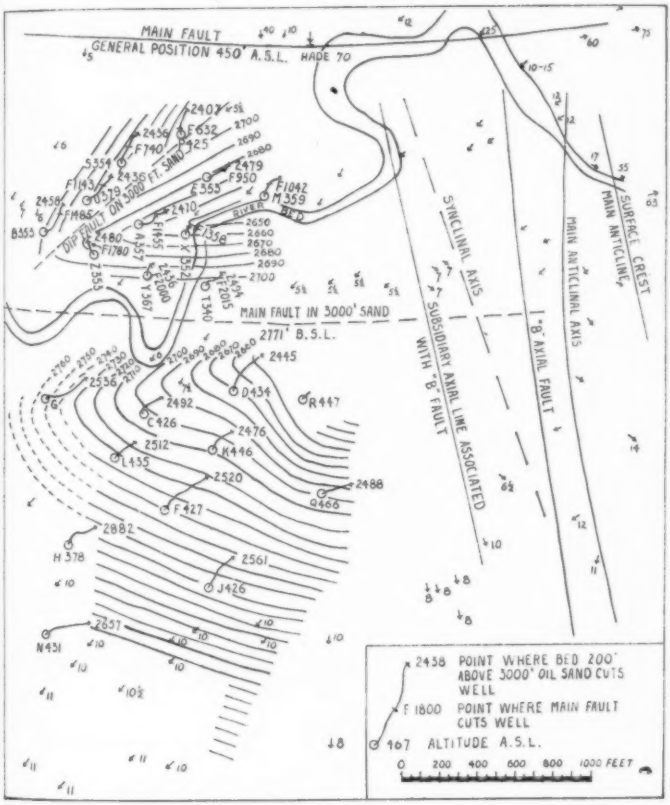

MAIN FAULT
GENERAL POSITION 450' A.S.L. HADE 70
MAIN FAULT IN 3000' SAND
2771' B.S.L.
SYNCLINAL AXIS
SUBSIDIARY AXIAL LINE ASSOCIATED WITH 'B' FAULT
'B' AXIAL FAULT
MAIN ANTICLINAL AXIS
SURFACE CREST MAIN ANTICLINE
DIP FAULT ON 3000 FT. SAND
2438 POINT WHERE BED 200' ABOVE 3000' OIL SAND CUTS WELL
F 1800 POINT WHERE MAIN FAULT CUTS WELL
107 ALTITUDE A.S.L.
0 200 400 600 800 1000 FEET

FIG. 17.

STRUCTURE MAP. ABRIDGED FROM MAP BY S. L. V. MAINPRISE. (NAMES OF LOCALITIES OMITTED.)

The structure shown in Fig. 17 is Pegu (Miocene), and the strata are strongly marked, the dip being generally less than 20°.

There are also mechanical reasons why rotary holes should deviate in an up-dip direction when the dip is below a certain critical angle which depends on the formation and on the type of bit. There is a tendency, when the critical angle is exceeded, for strike deviation ; usually to the right of one facing up-dip, the well frequently starting off in this direction.

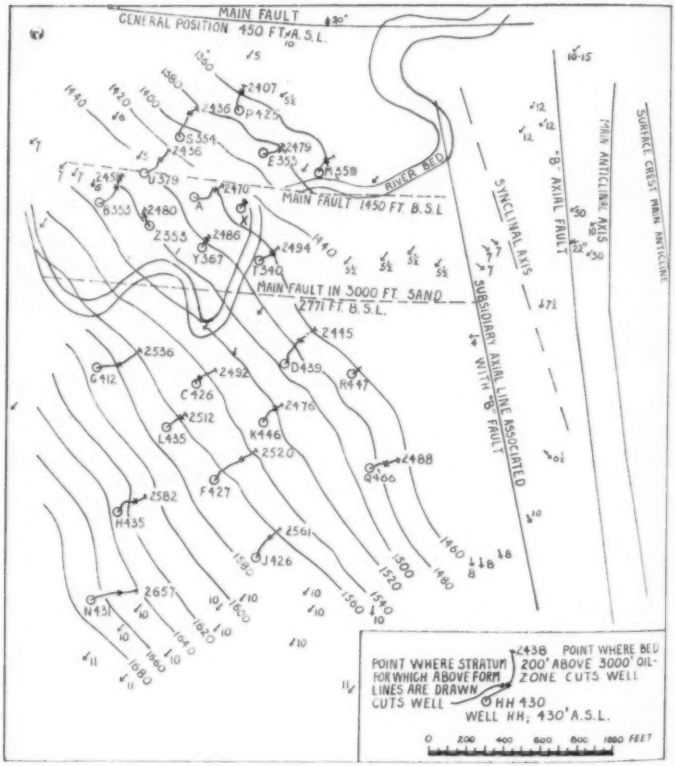

MAIN FAULT
GENERAL POSITION 450 FT. A.S.L.
RIVER BED
MAIN FAULT 1450 FT. B.S.L.
MAIN FAULT IN 3000 FT. SAND
2771 FT. B.S.L.
SYNCLINAL AXIS
SUBSIDIARY AXIAL LINE ASSOCIATED WITH 'B' FAULT
'B' AXIAL FAULT
MAIN ANTICLINAL AXIS
SURFACE CREST MAIN ANTICLINE
POINT WHERE STRATUM FOR WHICH ABOVE FORM LINES ARE DRAWN CUTS WELL
2438 POINT WHERE BED 200' ABOVE 3000' OIL-ZONE CUTS WELL
HH 430
WELL HH; 430' A.S.L.
0 200 400 600 800 1000 FEET

FIG. 18.

UNDERGROUND CONTOUR MAP. FORM LINES AS MIGHT BE DEDUCED FROM DEVIATIONS WITHOUT THE AID OF WELL-SLIPS CORRELATIONS. (FOR CORRECT CONTOURS SEE FIG. 17.)

The Author has been informed that when dips are very steep, holes are liable to deviate in a down-dip direction ; probably another critical angle could be found experimentally for a given set

of conditions ; but he has not sufficient data to give a rough idea of this angle.

It will be shown that the direction of strike deviation is likely to depend on the direction of rotation of the bit in the case of rotary equipment, and on the lay of the rope in the case of cable equipment. It is accordingly inferred that a hole deviating in a strike direction could in some cases be straightened by using a rope of the opposite lay or reversing the direction of rotation. This remedy is not always applicable, for left-hand threaded drill-pipe or tools are not usually available.

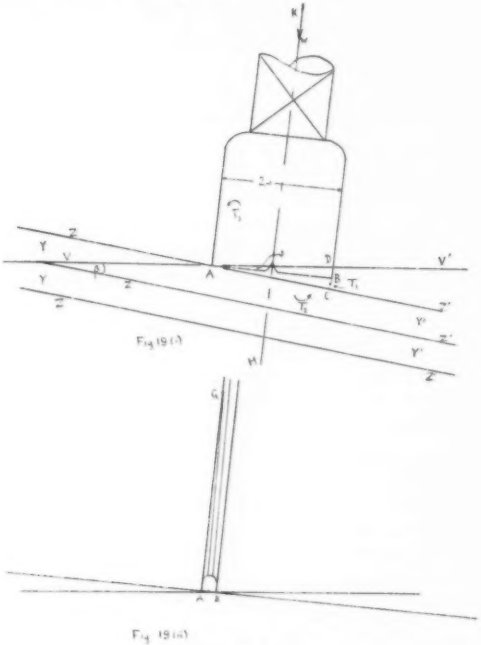


FIG. 19 (i & ii).

The holes shown were drilled in the usual manner ; that is, rotary equipments rotated clockwise (looking down), and left hand lay ropes were used for cable drilling.

In Fig. 19 a rotary bit is assumed to be drilling into a horizon which consists of a number of planes Z′Z on which and between which is homogeneous material YY′.

The planes ZZ′ are inclined at an angle β to the horizontal.

In the limit we may make the number of planes ZZ′ as large as we please, and the distance between them as small as we please, the object being to obtain a rough mathematical equivalent of a stratified rock.

We shall suppose that the bit will drill in the momentary direction of its axis, although its axis may be continually changing its direction. This is an assumption which cannot necessarily be made with all types of bit, but is probably nearly true for most of the commoner types.

Let AOB be the cutting edge of a fishtail bit, the axis of the bit being the line HOK, perpendicular to AB, which cuts AOB at 0. Let VV′ be the horizontal plane through A.

If the bit be lowered on to the inclined plane ZZ′, one side of the bit will meet the plane at A. There will then be a torque (T_1) tending to turn the bit into a position so that its axis HK is at right angles to the plane ZZ′; and this torque$=W\frac{AB}{2}$ where W is the downward thrust acting in the direction of the axis of the bit.

There will also be a force causing the bit to slide down the plane ZZ′. We shall suppose that unless the critical angle is exceeded this force will be balanced by friction and that no sliding will take place.

The torque T_1 will cause the drill-pipe to bend so that it may or may not rest against the casing. Assume, first, that the drill-pipe is not bent so much that it touches the casing at any point near the bit. There will then be a torque T_3 tending to restore the bit to the vertical position, which torque will be partly due to gravity and partly due to the bending of the pipe.

When the axis of the bit is at right angles to ZZ′, the torque $T_1=0$; but the bit cannot drill steadily at right angles to the plane ZZ′ because the torque T_3 would cause a reaction; so that the bit would continue to drill itself to a more vertical position. It will, in fact, take up a position between the vertical and the position at right angles to ZZ′.

With centre A and radius AB draw a circle cutting ZAZ′ at C and VAV′ at D.

The space ABC will be filled with the supposed homogeneous material YY′, which will, we shall suppose, reduce the effective value of the torque T_1, providing an opposing torque T_2, due to the reaction between the plane ZZ′ and the material YY′ underneath the bit, such that $T_1=T_2+T_3$.

Now if we consider the bit and the material immediately underneath it as a single mass being pressed against the plane ZZ′ by the torque T_1 it can be seen that there will be no torque due to reaction

between the said material and the bit, and hence that the bit will continue in the direction of its axis without turning, if $T_2=T_3$.

It seems reasonable to suppose that T_2 will vary directly as the weight or thrust on the bit W, as its width (AB) and inversely as some function of the depth of the material YY′ over the plane ZZ′ (that is, as the arc BC). Later, in the limit, we can merge YY′ and ZZ′ as already explained.

T_3, the restoring torque, may be considered as varying as the angle through which the drill-pipe is deflected, this being assumed to be small. It will be partly made up of the torque due to the drill-pipe treated as a spring and partly of the torque due to the weight and inclination of the drill-pipe. Let $T_3=k_1 \cdot \phi$ where ϕ is the angle which the axis of the bit makes with the vertical and k_1 a constant.

k_1 will be small when the hole is very shallow, when the bit is only kept in the vertical position by the weight of the drill-collar and a small amount of drill-pipe. It may also become reduced when at great depth the restoring torque due to the spring of the drill-pipe may be small. In some circumstances the drill-pipe may be held by a crook in the hole higher up, so that the spring of the pipe may be tending to pull the bit out of the vertical, thus having the effect of reducing k_1. Heavy drill-collars are advantageous in that they would increase k_1 by lowering the mass-centre of the drill-pipe. Also the use of heavier and bigger diameter drill-pipe increases k_1.

For the sake of argument, assume that T_2 varies as the length of the arc BC, and hence as the angle which the axis of the bit (HK) makes to the line drawn perpendicular to the plane of the horizon ZZ′ $(=\beta-\phi)$, and let $T_2 = \dfrac{l_1.\text{W. (AB)}}{\beta-\phi}$ where l_1 is an unknown constant depending on the type of formation.

Then, when $T_2=T_3$

$$k_1.\phi = \frac{l_1.\text{W. (AB)}}{\beta-\phi} \quad \begin{pmatrix} \phi=\text{inclination of the bit.} \\ \beta=\text{inclination of the stratum=dip.} \end{pmatrix}$$

$$\text{whence } \phi = \frac{\beta}{2}\left(1 \pm \sqrt{1 - \frac{4\,l_1.\text{W. (AB)}}{k_1.\,\beta^2}}\right)$$

$$= \frac{\beta}{2}\left(1 - \sqrt{1 - \frac{l.\text{W.}}{k.\beta^2}}\right) \quad \ldots\ldots\ldots\ldots\ldots (1)$$

where k is a constant depending on the characteristics of the drill-pipe and increasing with the ratio $\dfrac{\text{diameter of drill-pipe}}{\text{diameter or width of bit}}$ and l depends on the type of formation which is being drilled. The negative sign is used as this position is likely to be approached

first, when equilibrium would be maintained unless the weight (W) on the drill was allowed to become excessive. It is to be noted that

(1) When β, the dip, is small, ϕ is likely to have no real value.

(2) When k is small, ϕ is likely to have no real value, and this will occur when the drill-pipe is too weak, or at the commencement of the hole, or possibly at great depth.

When ϕ has no real value, if we still assume that until the critical angle is reached no sliding will take place, it can be inferred that the hole will stay in an up-dip direction, proceeding in a series of waves.

When the critical angle is exceeded, the bit will slide down-dip and bite against the down-dip side of the hole. It is suggested that the bit would then be drawn in a strike direction, to the right (Fig. 9, pts. l, m, n), the amount of deviation varying with the weight on the bit, which would in the case of hard formations usually be small. It is possible that the critical angle becomes reduced in the case of very hard or very soft formations: in the case of extremely soft formations such as are likely to be found at or near the surface the hole would deviate irregularly. The bit may proceed through comparatively soft formation to some considerable depth and then suddenly encounter harder stuff when, the critical angle being no longer exceeded, the hole would change its direction and proceed up-dip, possibly as in Fig. 4, pts. i, j, k, l, m, n, o, p; or there may be a more gradual change as is possibly exemplified in Fig. 2, pts. a, b, c, d, e, f. There is always the chance of the existence of a small irregular hard patch, or a boulder. After passing a hard patch holes seem to show a tendency to turn back and continue in prolongation of their original direction or curve (Fig. 9, pts. l, m, n, o, p; Fig. 16, pts. l, m, n, o, p). This tendency is remarkable and occurs also after sidetracking. The tendency for strike deviation would depend a great deal on the type of bit used, the ordinary fishtail being most liable to be drawn in a strike direction, and such a bit as the Zublin the least. Examples are Fig. 2, pts. a, b, c, and Fig. 13, pts. p, q, r, s.

If the pipe is caused to touch the casing as at G in Fig. 19 (ii.), so that a reaction is caused at B, the side of the bit furthest away from the point G at which it might touch, there would be a tendency for the bit to dig in and jamb at B, and for the bit to be drawn over so as to incline itself in a strike direction as above. The pipe will naturally bend itself so as to cause the minimum strain on itself as it revolves, that is, away from that side of the pipe which is in compression. Assuming the top of the pipe to be vertical, the jambing would take place at B, not at A (see Figs. 19 (i.) and (ii.)).

Referring to the formula (1) given above, if the formation is hard, l will be large. Since, however, W will normally be reduced

—automatically in the case of Hild drive equipments—the hardness of the rock will not necessarily have any effect on the amount of deviation. When the rock is exceptionally hard and tough the reduction of W may be the predominating factor, thus causing a reduction of deviation, as is illustrated in Figs. 8, 9 and 13.

When drilling with percussion or cable equipments, we may consider that when the bit strikes the bottom of the hole, a torque is imparted to it (T_1) due to its hitting the supposed inclined plane ZZ′ of a stratum (Fig. 20). This torque causes the bit to incline itself to the vertical during a blow, so that it may or may not hit the side of the hole or the casing higher up, as at G (Fig. 20).

The amount by which the bit becomes inclined during the blow depends on the duration of the blow and on the inertia of the bit, as well as on the dip. Assuming that the length of the stroke is not altered, a softer stratum would perhaps lengthen the duration of the blow and probably reduce T_1; so that the direction of the hole would not necessarily be altered in passing from hard to soft strata and vice versa.

The suggestion is that if the bit or augur stem does not hit the side of the hole, during the stroke, at some point such as G (Fig. 20), the hole will deviate in an up-dip direction (see Fig. 15). If it does, that the bit will be caused to dig into the opposite side (at A, Fig. 20). Owing, then, to the fact that the bit is turning the hole will tend to deviate in a strike direction. If a rope with a left-hand lay is used, the tool will be turning clockwise in plan, and the hole will deviate to the left facing up-dip. (See Figs. 3, 14 and 16.)

The bottom of the hole would be curved in section, as AOB in Fig. 20.

In the case of both cable and rotary equipments, strike deviation should be more difficult to control than up-dip deviation, if the amount of the latter is definitely controlled by the dip of the strata.

Fig. 13 is an example of a hole drilled with worn and probably weak drill-pipe. Fig. 3 is an example of a hole, the plan view of which shows the deviation to turn from a strike direction into an up-dip direction. The dip here is about 11°. The change occurs remarkably suddenly at the point where the method of drilling was altered, showing that the critical angle for cable equipments is likely to be below that for rotary equipments. Fig. 16 shows a cable hole probably starting off in a strike direction and finishing in approximately an up-dip direction. Here the dip at depth is known to be less than the surface dip. In the case of holes J and K, it was possible to obtain fairly exact measurements of the direction of the dip at the surface; and both holes seem to start off in an almost exactly up-dip direction (see Figs. 7 and 8).

Hole B (Fig. 2) starts off in a strike direction, turning gradually into an up-dip direction.

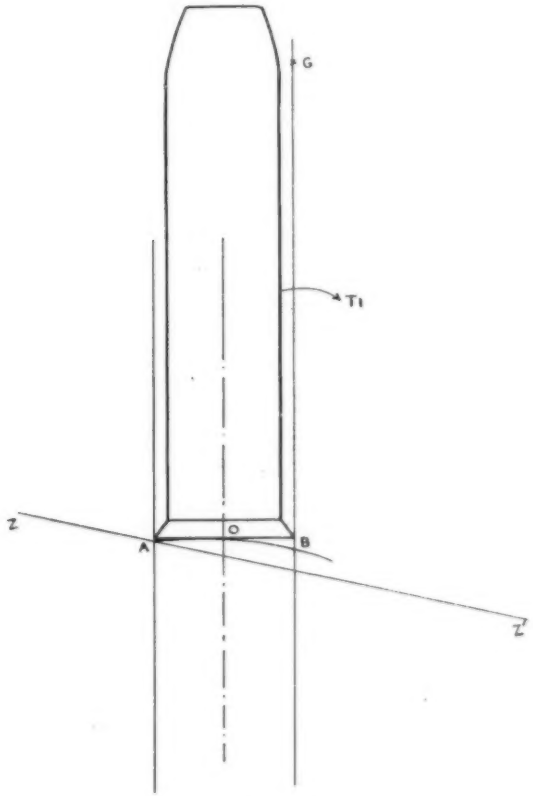


FIG. 20.

The effect of sidetracking in the wells which have been surveyed has been to make a kink in the plan view of the hole, but not to alter the general direction. The effect will usually be a kink to the left, facing the direction in which the hole is going (Figs. 1, 2 and 6). This is probably due to the direction of rotation in the case of rotary tools, or to the lay of the rope in the case of cable tools. The bit may be expected to slide off the object, usually in a down-dip direction ; it would then bite against it and be pulled

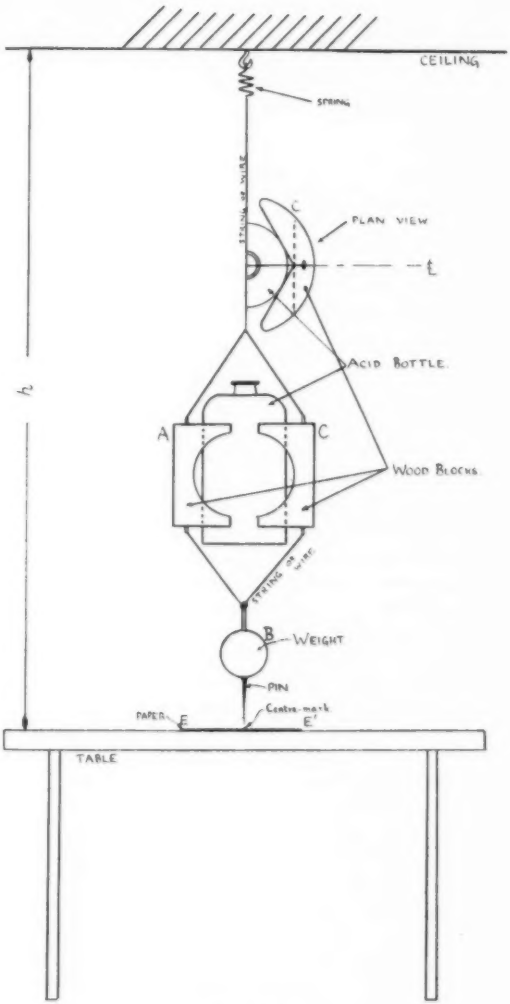


FIG. 21.

APPARATUS FOR MEASURING ACID-BOTTLE INCLINATIONS.

to the left (Fig. 6, pts. *m*, *n*, *o*). Subsequently it turns and continues in prolongation of its original direction or curve. This is shown in rather a striking manner in Fig. 1, pts. *h*, *i*, *j*, *k*, *l*, *m*, *n*, *o*. The effect of using weak drill-pipe is to reduce *k* in equation (1). Only one example is given of this (Fig. 13). The irregularity in the deviation of this hole is interesting when compared with the others. There seems to be a general tendency for holes to retain their direction of deviation, and not to deviate irregularly.

Wells drilled for freezing ground in shaft-sinking operations are so close to one another that it has been suggested that the deviation of one well might affect the deviation of another. This may or may not be the case. Such wells seem also to tend to deviate in straight lines. The only example I know of wells being drilled in this manner to any depth is that given in Fig. 2, p. 7, of "Deep Borehole Surveys and Problems," by Haddock. This shows the plan view of a number of holes drilled to a depth of 1700 ft. The formation here is not known for certain, but is believed to be igneous rock and volcanic tuff.

The holes deviate irregularly, in all directions.

II.

While it is true that rough non-directional measurements of inclination can be made with ease, the problem of surveying an oilwell and obtaining a result which can be regarded as certain and accurate presents considerable difficulty.

The first main difficulty which presented itself was the problem of guides. The guides of any inclinometer must ensure that its central axis shall be parallel to the general direction of the hole at a given point. Also, they must not be liable to stick in the hole. The Martienssen inclinometer is provided with brush guides as shown in Figs. 34 and 35. They are cylindrical brushes and are only intended for use in cased holes, which they must fit exactly, so that a number must be provided for different sizes of casing.

These guides were used in the first few holes surveyed, but were always a source of anxiety. Occasionally they would refuse to allow the instrument to go beyond a certain point into the hole; this might have been due to elliptical casing or to cement or mud adhering to the casing. One was never sure of being able to pull out without trouble; although, in fact, they never did stick in a hole so much as to cause difficulty of this kind.

It was desired to use the declinometer in open hole full of mud as well as in cased holes full of oil or water or empty; often holes would be gassing. The brushes would work satisfactorily in clean

cased holes full of water ; they were, however, liable to collect mud and oil, and so cause errors in cased holes not in clean condition.

The sides of uncased holes were likely to be irregular. They would always be full of fairly heavy mud. The brush guides provided would be likely, if used in such holes, to collect mud and to stick on any obstruction, as will be seen from the photographs (Figs. 34 and 35).

It is easy to make guides which will give a rough idea of the inclination of a hole when this is 10° or over ; but when the inclination is 3° or less, or, as sometimes, 1° or less, the problem becomes more difficult, as any irregularity in the side of the hole might cause a totally erroneous impression to be obtained of the general direction of the deviation of the hole.

For reasons already explained, it was desired to be certain of obtaining small angles with fair accuracy.

The use of spring guides was thought to be objectionable, owing to the exactness of manufacture and tempering which would be necessary if accuracy were required for reading small inclinations of a degree or less ; also, it is very difficult to make such guides in a form which is not likely to collect mud or to stick in an open hole.

The first improvement attempted was the manufacture of a pair of brush guides having steel bristles (Fig. 33) spaced fairly widely. These were made in Burma and proved satisfactory in cased holes—they were not intended for use in open hole. They collected far less mud and dirt, and were not so liable as the original type of brush to register false inclinations on account of mud clinging to the side of the casing.

The next step was to try dispensing with guides, allowing the instrument to slide freely along the lower side of the hole. Special " torpedo-heads " were made of brass to fit the top and bottom of the containing cylinder, a very small clearance being made on the diameter in order to prevent the steel of the cylinder from touching the casing. This was done in order to reduce magnetic effects, which will be discussed later.

A short extension was added to the top " torpedo-head " (Fig. 32). This has the effect of allowing the instrument to align itself with the hole normally ; should, however, great irregularities be present, or the inclination of the hole be very small, the instrument would have an increased tendency to align itself with the cable at the point of suspension. In this way small irregularities would not prevent small angles of inclination, such as 20 minutes or less, from being read with reasonable accuracy.

One object of this arrangement was to avoid the use of a large number of brushes and to provide an apparatus which could be

used in any hole of any diameter, cased or uncased, thus making for speed and certainty without losing, and possibly gaining, accuracy.

Before a survey the apparatus had to be supported over the hole and lowered into its containing cylinder. The guides had to be screwed on and the water-excluding glands tightened up while the apparatus was held over the hole and immediately before lowering. As the gyro-compass must not be disturbed, the cylinder had to be held rigidly. The absence of the lower brush fitting the hole increased this difficulty so much that special adjustable clamps were designed and made to work in conjunction with a rigid framework. In Figs. 26 and 27 the clamps and the framework for holding the apparatus over the hole are shown. The framework could be quickly taken to pieces for transportation purposes.

A cased hole was surveyed twice, first using brushes and then the torpedo-head arrangement. Both surveys agreed remarkably exactly. The torpedo-head arrangement was then tried in an uncased hole, and good curves were obtained. There was, however, a fair amount of irregularity in the readings obtained from the uncased hole, readings near the same place—say, 4 to 6 ft. apart—varying by from 15 to 20 per cent.

It was accordingly proposed to manufacture a longer lower torpedo-head (see Fig. 30), so as to increase the length of the apparatus by from 100 to 300 per cent. or more, and to increase the length of the extension (as in Fig. 31). We were, unfortunately, unable to try this, but there is little doubt that open holes could be surveyed accurately in this way, bearing in mind that the length of the apparatus as used was only 7 ft.

Practically the only danger of losing apparatus of this form in open hole is that of the hole caving in on top of it. The risk of this will usually be known.

The ratio of the diameter to the length of an oilwell is such that it would usually be sufficient to survey the path of a supposed thin string passed through it and stretched tightly. An error in total deviation of a few inches such as might occur through the instrument not being centred in the hole, but, rather, being allowed to lie on one side, would ordinarily be negligible. Occasionally it is desired to survey a hole with such accuracy that another hole may be drilled down vertically to meet it in order to avoid a crook. Special measures to ensure accuracy would then have to be taken suitable to the particular circumstances. It would be known on which side of the hole the instrument would lie, and allowance could be made accordingly.

If a cylinder hanging in a hole of greater diameter than itself rests on an irregularity projecting from the side of the hole, it will be inclined at an angle which depends on the point on the cylinder which rests against the side of the hole.

In Fig. 22A, the declinometer, having central axis AB, rests on the side of the hole at a point P′, and is hanging from a cable

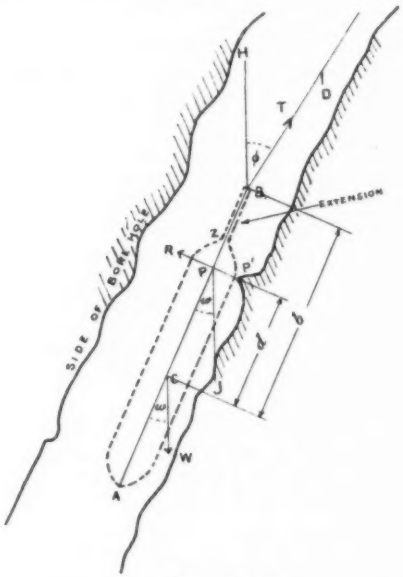


FIG. 22 (A).

DECLINOMETER, SHOWING CONDITIONS FOR MAXIMUM ERROR IN INCLINATION MEASURED.

ZB = Extension.
C = Mass-centre of declinometer.
AB = Central axis.
BD = Cable.
P′ = Point on which the declinometer is resting.
BH and PJ are vertical.

$$\phi - \omega = \omega \frac{d}{b-d}$$

BD. The mass-centre of the declinometer is at C. Let P′PR be drawn at right angles to AB to represent the reaction R at P′. Draw HB, PJ vertically through B and P.

Let the tension in the cable at B = T.

Let the weight of the declinometer = W, acting at its mass-centre C. Let CP = d. Let CB = b. Let $\angle HBD = \phi$, $\angle JPA = \omega$. Resolving along AB, we have:

$$W. \cos \omega = T. \cos (\phi - \omega).$$

Taking moments about P :

$$d.\mathrm{W}.\sin\ \omega=(b-d)\ \mathrm{T}.\ \sin\ (\phi-\omega).$$

For small angles of inclination (ϕ and ω not greater than about 10°):

$$\frac{\mathrm{W}}{\mathrm{T}}=\frac{\cos\ (\phi-\omega)}{\cos\ \omega}=1, \text{ and } \frac{d}{(b-d)}=\frac{\sin\ (\phi-\omega)}{\sin\ \omega}=\frac{\phi-\omega}{\omega}$$

that is $(\phi-\omega)=\dfrac{\omega.d}{b-d}$

(Note that if the point P is below C, d becomes negative.)

If, therefore, it is desired to prevent $(\phi-\omega)$ becoming large, d must be kept small. The extension ZB is designed to have this effect.

It would be possible by increasing the length of the extension ZB relative to the length of the cylinder to make the instrument very nearly align itself with the cable at the point of suspension. An acid-bottle container in the form of a torpedo having an extension as in Fig. 22B would within a very small error align itself with the cable. In this way a tangent to the hole at a point higher up is measured. The inclinations are then plotted against the length of the hole, the actual positions of the container being used. The correct curve for the hole can then be deduced from the curve so obtained, knowing the diameter of the torpedo and that of the hole.

This method has the advantage that fairly exact checks should be obtained in a hole having very irregular sides, and that a single reading obtained with an acid-bottle should give a fairly certain indication of the inclination of the hole.

Usually in cased holes a cylindrical inclinometer would slide along the lower side of the hole ; if provided with a short extension it would tend to align itself with the cable where irregularities existed (Fig. 32).

The next difficulty was found to be connected with the cable. The necessity for the use of a cable embodying 8 insulated copper wires and a steel core will be explained later ; and in order to do this it is necessary to describe the apparatus itself and the reasons why simpler apparatus or apparatus requiring no electrical connection to the surface could not be used.

The cable connecting the declinometer apparatus consisted of 8 rubber-covered copper conductors surrounding a rubber-covered steel core. The whole was surrounded by covering of very tough material which was heavily impregnated with tar. About 72 per cent. of the cable by weight consisted of insulating material and the external diameter was about $1\frac{1}{8}$ in. It weighed approximately 0·6 lb. per ft. run, and the breaking load when new was found

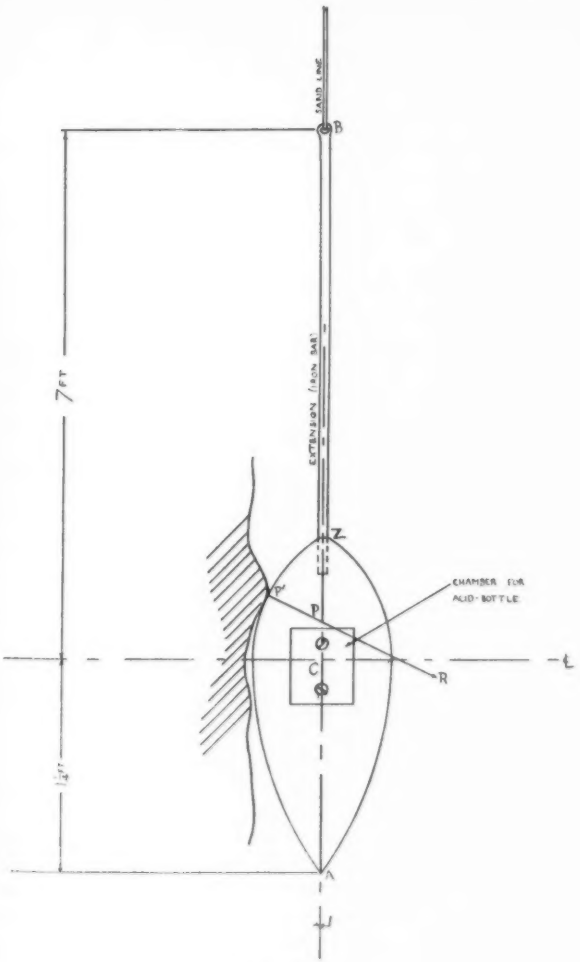


FIG. 22 (B).

ACID-BOTTLE CONTAINER.

ZB = Extension.
R = Reaction at P'
AB = Central axis.
C = Mass-centre.

% error = $\frac{CP}{PB} \times 100$, assuming that the sand line near B is taut and in the direction of the hole At the point (higher up) where it rests against the side of the hole.

to be 6720 lb.=the weight of a length of about 11,000 ft. It was designed for use under water.

It was found to be necessary to use the cable under water and oil, sometimes under oil, and sometimes in empty holes. Crude oil dissolves both rubber and pitch and tar. Gas containing compounds of sulphur would affect the rubber. It was therefore thought advisable to coat the cable with some material before use in any liquid containing gas or oil. It was found that shellac formed a useful and flexible coating; but it washed off in the first hole surveyed. It was found, however, that if the shellac was put in while the cable was hot and the tar was liquid (Fig. 37), it would form a hard compound with the tar which would last much longer. Immersion in thick mud had a beneficial effect in mudding off the oil in subsequent surveys.

In an empty hole a small trickle of water, insufficient to damage the hole or to affect it in any way, was kept running down the cable during a survey. This prevented fraying and washed oil off.

The steel core of the cable is invisible throughout its length, and it showed a slight tendency to rust. It is understood that this difficulty will be overcome by causing an extra thick coating of tin or nickel to be deposited on the steel. However, it would seem advisable to make the well water slightly alkaline before a survey. This difficulty was not solved satisfactorily in Burma. Glands and pitch were used to exclude water so far as possible.

Owing to the weight of the cable (see above) it was not thought advisable to survey empty holes much below 3000 ft. In mud or water, however, holes could be surveyed to over 5000 ft., the limit being set by the strain on the outer case due to the pressure. The cable weighed $\frac{1}{3}$rd of its weight in air, under water, and was liable to float in very thick mud. The inclinometer itself weighed from 100 to 150 lb., depending on what types of guides were used.

When possible, wells were surveyed after cementation and prior to drilling through, when the hole could be filled with water. It was, however, found that wells were then rather liable to have obstructions, possibly of cement, adhering to the sides of the casing.

Most of the remaining difficulties were connected with the gyroscope in one way or another. It is proposed, therefore, before proceeding further, to explain the reasons for the use of the Martienssen apparatus and to describe the apparatus itself.

Magnetism is always likely to be present in both cased and uncased holes, and the magnetic compass is not favoured for accurate work; although there are a number of valuable inventions for obtaining approximate results in uncased holes employing the magnetic compass. The Martienssen apparatus is provided with a gyroscope for obtaining direction and two pendulums for obtaining

inclination. For the sake of comparison, most apparatus designed for the survey of boreholes may be considered under the following main headings :—

1. Those which employ a magnetic compass to obtain direction.
2. Those which employ a gyroscope to obtain direction.
3. Those which employ seismic methods.
4. Those which employ surface orientation methods.

And, further, as follows :—

(*a*) Methods which rely on the measurement of the position of the surface of a liquid relative to the sides of its container for obtaining inclination.

(*b*) Pendulum methods for obtaining inclination.

The methods of recording the readings so that they may be observable at the surface may be considered in general under the following headings :—

(i.) Those in which the liquid solidifies or makes a mark on the side of its container.

(ii.) Those in which pendulums prick charts.

(iii.) Photographic methods.

(ii.) And (iii.) may also be (*x*) operated mechanically, or (*y*) operated from the surface.

(iv.) Methods in which the position of the instruments below is conveyed electrically to a machine at the surface by a series of impulses or otherwise; also, resistance methods which usually employ a Wheatstone bridge so that with telephones the position of the surface of a liquid—for example, mercury—can be read at the surface.

The advantage of using a gyroscope for obtaining direction is that it should not be affected by magnetic influences.

Magnetic, electromagnetic and electrostatic conditions existing at the bottom of a deep hole are almost always unknown. In any particular hole they probably vary from time to time and depend on the amount of casing, if any, which is present, and the length of time which may have elapsed since the cessation of drilling operations. Casing is almost always strongly magnetised. Nearly all steel accessories which are present on a rig where drilling is being carried out are likely to be fairly strongly magnetised. The friction at the bit will most probably cause electric currents to flow in the earth and along the drill-pipe and casing; these may continue in the earth and along the casing for some long time after drilling has ceased. A condition of strain is set up near the hole causing subsidences and movements; water may be released from one horizon to another; and not only are electro-chemical actions likely to take place, but also casing, if present,

may behave as the terminal of an electric cell. The result is that a magnetic compass cannot be used safely in either cased or uncased holes, even when iron pyrites are known to be absent. Casing in nearby wells is also a possible cause of magnetic disturbance.

In cased hole, the magnetic field at depth is sometimes intense.

Pendulum methods for obtaining inclination are preferred to acid-bottle methods; they are more accurate, and it is easier, with pendulums, to arrange for a number of readings to be taken in the course of one run.

The great advantage of photographic methods is that the instruments below can be light, without the necessity for any following-up gear; their relative positions can be photographed without disturbing their position or setting. In consequence, the external diameter of the container cylinder can be reduced.

Surface orientation methods are uncertain in very deep boreholes. The difficulty is the calculation of the allowance to be made for the angle through which the apparatus below may have turned. This angle cannot necessarily be obtained by a process of simple addition, since it is a function of any twisting or spiralling done by the hole itself. Surveys by the Martienssen method, however, show that in most cases very little spiralling is present.

It is not thought that seismic methods will be used much in future. In cases where the deviation is known to be large, they are useful.

The Martienssen apparatus is provided with a gyro-compass, and has two pendulums for obtaining inclination. These pendulums have their axes fixed at right angles to one another. When a key is depressed at the surface, they are caused simultaneously to prick two small holes in each of two charts, so that their position is recorded. A motor energised through floating contacts fixed on the gyro-compass (Fig. 39) drives the box which contains the pendulums and charts, so that it is caused to follow up the movements of the gyro-compass. The directional inclination of the central axis of the apparatus to the vertical is calculated from the readings so obtained. Each time that the key is depressed, the pricks are made and the charts move on; as the latter are in roll form, an almost unlimited number of readings may be taken in one run. These readings can afterwards be identified by another marking arrangement for which another key is provided, and by means of which a mark can be made against any desired reading.

The apparatus is provided with a wagon which contains everything and when loaded weighs rather over 7 tons (Fig. 23). Winding gear is provided, with a cable; 5000 ft. of the cable weigh about a ton and a half. The cable has 8 rubber-covered

copper conductors surrounding a steel core. Generators supplying direct current at 100 volts for the marking gear, and supplying 400 cycles A.C. at 100 volts for the gyroscope, are provided. Movement of the gyro-compass can be detected by means of ammeters which measure the current passing through the armature of the said motor which drives the pendulum-box, the "follow-up" motor. The eight copper conductors are used as follows:—

Nos. 1, 2 and 3.—Carry three-phase current to the gyroscope (400 cycles, 100 volts).

Nos. 4 and 3.—Recording mechanism. (Current for pricking the charts.)

Nos. 5 and 3.—Marking mechanism. (Identification of readings.)

Nos. 6, 7 and 3.—Current flowing through the double armature of the follow-up motor.

Nos. 8 and 3.—Field current of the separately excited follow-up motor.

The weight of the loaded wagon containing the apparatus (7 tons) and particularly the size and weight of the cable make it somewhat unwieldy. This difficulty should be overcome with proper modification of design.

The apparatus is capable of doing surveying work accurately and thoroughly. A survey can be completed to 3000 ft. in about 6 hours, including rigging up and packing up. If a well in the process of being drilled is surveyed about once a month, of course fewer readings need be taken, and the time can be reduced. About 50 readings would normally be sufficient, including checks, in a hole 3000 ft. deep. The time is mostly occupied in waiting for the gyro-compass to settle down. The process of settling down can be accelerated by manipulation of the follow-up motor controls.

The Martienssen gyroscope forms the rotor of an induction motor. The motor itself is fitted with a windage cover, so that it is totally enclosed and not affected by air currents caused by its motion. The whole floats in mercury, being suspended from a steel float. The latter was replaced in Burma with a non-magnetic float made of bakelite. The rotor is solid, consisting of copper embedded in steel. It rotates at 23,000 r.p.m. The wound stator is situated within the rotor, and is supplied with 3-phase 400-cycle current at a potential of 100 volts. Current is supplied to the floating mass through four light silver bands, one being connected to the floating contact through which the follow-up motor is energised.

The gyro-compass has certain characteristics which make its behaviour differ very much from that of a magnetic compass. It entirely depends for its orientation on the motion of the earth. Therefore, speaking generally, any other motion will disturb the compass; such, for example as raising or lowering the apparatus in a borehole the sides of which are not smooth. The period of a magnetic compass over a complete swing may be of the order of from 1 to 5 seconds; that of the Martienssen gyro-compass is 15 minutes in Burma, this being a function of the latitude. The ratio of the restoring torque to the weight of a gyro-compass is so small that an ordinary pin-bearing would not be satisfactory; the restoring torque of the Martienssen gyroscope with its axis held east and west in a horizontal position would be a fraction of a gramme-centimetre, the effective torque being much less than this. The period is a function also of the distance of the mass-centre of the floating or hanging mass from the point of suspension, "the eccentric distance." A gyroscope suspended at its mass-centre would have no restoring torque and would not act as a compass. Such an "astatic" gyroscope can be moved about readily without being disturbed; and the practice is to make the eccentric distance of ships' gyroscopes comparatively small, so that the period of the compass should be large compared with the rolling period of the ship.

Getting the gyro-compass to swing freely at depth proved to be one of the greatest difficulties. Unless the period could be checked, some doubt necessarily existed as to whether the compass might have aligned itself correctly in the north-south meridian. At some tests at Wietze, Germany, in 1930, the compass could not be made to move freely at depth in a cased hole, and the results of surveys did not agree very exactly.

Previous to this, similar apparatus had been working very satisfactorily in holes drilled for shaft-sinking by the freezing process, such holes being usually not deeper than 500 to 1000 ft. and having as a rule very small inclinations. In taking the apparatus straight from these Wietze tests out to Burma, the Author was compelled to take the risk of being able to make the gyro-compass work satisfactorily; time did not admit of changes.

On attempting, in Burma, to solve this problem, it was realised that there were a number of ways in which the gyro-compass might be prevented from moving freely at depth; but it was not clear as to why this fact had not been discovered before. Perhaps it had not been necessary to deal with very inclined holes—more than, say, one or two degrees—and perhaps much magnetism was not present in the holes which had been tested.

The movement of the gyro-compass might be affected :—

(1) By the existence of magnetic material on the floating mass ; it will be remembered that the gyro-compass consists of a little electric induction-motor hanging from a circular float in mercury.

(2) By the forces on the floating contact.

(3) By friction on the mercury itself, possibly due to the formation of a scum.

(4) By the electrical connections to the floating mass.

Before proceeding to Burma, a compass was ordered having as few parts as possible of magnetic material. Only the magnetic circuit of the motor had to be of magnetic material, and it was not thought that this could have effect on the orientation of the compass ; the continual passage of alternating current through the windings would prevent the existence of any permanent magnetism. A float of non-magnetic steel was ordered. It was felt that the compass might be drawn bodily over to one side and friction be caused against the centre-pin.

The action of the floating contact can be seen from an examination of Fig. 39. In order to watch the effect of the floating contact on the motion of the gyroscope, an electrical arrangement was devised by which the follow-up motor was caused to ring a bell at the surface once during each revolution (shown in Fig. 28), which latter corresponded to a movement of 50 minutes of the gyro-compass. The direction of movement could be watched by means of ammeters in the armature circuit of the follow-up motor already provided with the apparatus.

It was found that the shape of the floating contact was very important, and that fine wire without swelled ends (A and B), Fig. 39, making contact with and directly at right angles to the fixed contacts CD, C′D′ was the best arrangement. If the ends at A and B were swelled into little spheres, the gyro-compass would behave as if heavily damped and might fail to orient itself altogether. The plain wire contact, of platinum-iridium, 0·25 mm. diameter, could be made to draw the compass round with it if the voltage of the follow-up motor was raised too much. This would make the compass appear to be working frictionlessly.

Such a contact was originally used, and changed to the swelled-end type, it is believed, before the adaptation of the apparatus to oilfield work. It was not fully appreciated that the swelled-end type of contact would behave differently, and what was really the effect of the well-known readiness of the electric current to arc across from a point was put down to absence of friction. The direct current supplied to the follow-up motor would naturally

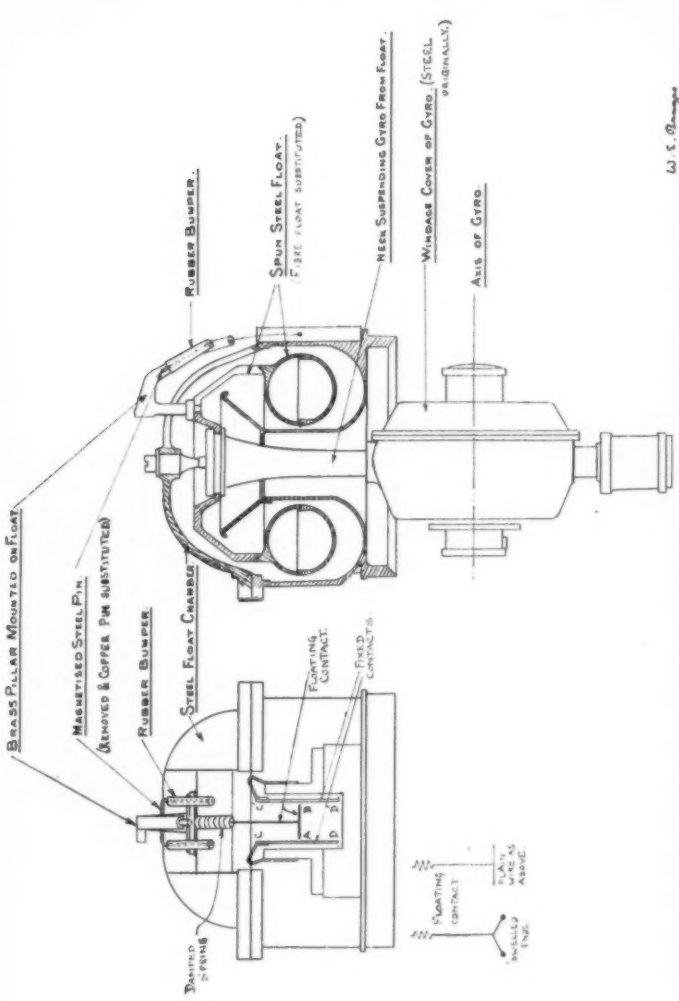


FIG. 39.

DESELINOMETER FLOAT AND FLOAT CHAMBER. (SO ILLUSTRATE MAGNETIC EFFECTS.)

continue to flow so long as it could arc across, which it could do more easily from a pointed or fine wire contact than from a spherical contact.

It was found that incorrectly arranged contacts might cause the gyro-compass to swing unsymmetrically about the meridian, so that it would be difficult to judge from the surface when the compass had oriented itself except by plotting, using the above-mentioned bell-indicator.

Probably the best form of contact is that in which the floating contact slides along an insulated surface in which the fixed contacts are sunk flush. This, however, introduces a little friction.

The friction in the mercury was reduced by proper treatment of the mercury and by the provision of a float made of fibre, much lighter than the steel floats provided.

The mercury was treated by heating it electrically and shaking or churning it with carbon granules, the latter being subsequently filtered off. It was kept in a high column, in a steel pipe moist with benzene when not in use.

It was found that arcing at the commutator of the follow-up motor and at the floating contact electrolysed the atmosphere inside the steel container. This reduced the pressure by causing the formation of oxides of nitrogen and ozone. This in turn encouraged the existence of oily vapour, and caused a scum due to oxidation and to oily deposit to form on the surface of the mercury which might cause the compass to be held. Ozone is a fairly powerful oxidising agent.

This difficulty was overcome by throwing a very small quantity ($\frac{1}{8}$ oz.) of benzene (C_6H_6) into the container immediately before a survey. The benzene vapour would be split up by electrolysis according to the equation :—

$$C_6H_6 = 6C + 3H_2,$$

causing increased pressure in the container and the formation of a small amount of atomic hydrogen, which is a powerful reducing agent. If too much benzene was used, an excessive amount of carbon appeared between the floating and fixed contacts. The addition of benzene in this manner had the effect of keeping the mercury in condition and preventing the deposition of oil on the light silverband connections to the floating compass.

The manufacturers now avoid the use of mercury by the use of a special bearing through which liquid is continually kept in motion by means of a pump. The latter is, however, an additional complication.

It was possible to test the truth of a survey by sending both gyro-compasses, magnetic and non-magnetic, in turn down a hole,

DECLINOMETER FLOAT AND FLOAT CHAMBER. (TO ILLUSTRATE MAGNETIC EFFECT.)

Fig. 30.

the magnetic compass, when tried, showing only very small differences but moving less freely. In both cases, steel parts likely to become permanently magnetised were removed. The non-magnetic compass moved freely at depth, so that it was possible to check its period; which proved to be the same as that obtained at the surface.

In some respects an astatic gyroscope is to be preferred for making surveys. The advantage is that the apparatus could be raised or lowered at almost any desired rate. If it were driven by batteries located inside the containing cylinder, and an automatic photographing arrangement made to act at known intervals provided, the connecting wires could be dispensed with and the apparatus could be lowered on a sand line. The Sperry arrangement is constructed somewhat on these lines, but a gyro-compass is used.

A disadvantage of the astatic arrangement is that the human element is introduced, together with a certain difficulty in setting it parallel to the earth's axis and checking it at the end of a survey. The Martienssen method is on this account to be preferred. It is usually possible to survey a well, cased or uncased, when the drillers are cleaning up, the delay being nominal.

It is not safe to employ a gyro-compass without some means being available of watching or detecting its movements. This involves electrical connections to the surface through a cable. The compass is less likely to be disturbed by the process of raising and lowering in nearly straight and vertical holes than in very inclined or crooked holes.

With regard to measurement of inclination, apart from direction, two pendulums were provided having their axes fixed at rights angles. Readings of inclination were obtained by means of pricks made on paper charts, as has been explained.

It was felt to be desirable that the pendulums should take up their positions without a variation of more than a minute, it being hoped to read inclinations to within three minutes. They were provided by the manufacturers with jewel bearings; they were made of brass, but had steel tips and pins for pricking the charts.

Brass pins and tips were manufactured in Burma and substituted for the steel ones. They were rather easily deformed, but were found to be necessary in cased holes because of existing magnetism.

Adjustment and treatment of pendulum bearings caused very little difficulty. If too tight, they would seize up owing to the higher temperature at the bottom of the hole. If too loose, they were liable to fail to operate satisfactorily if much inclined. A small amount of clock oil was found to be desirable. The adjustment was quite easy to make, and the arrangement is a very good

one for accurate work. In view of the extreme differences of temperature likely to be met with in boreholes, it is difficult to see how an improvement could be made on the manufacturer's arrangement.

Readings were taken every 150 ft. or so, and the inclination was assumed to be constant over the length of hole at the centre of which the reading was taken. The sine of the angle of inclination could be read directly from the charts, and the deviation in a north-south or east-west direction is the said length of hole multiplied by the appropriate reading.

It must be remembered, however, that there are small errors introduced by this simple method of calculation due to the fact that the axes of the pendulums are fixed at right angles to one another, and are in planes at right angles to the central axis of the instrument—that is, at right angles to the direction of the hole.

Neither pendulum is thus (in general) exactly in the vertical north-south or east-west plane.

Such errors are negligible unless inclinations exceed 10° or so.

It was found advisable to plot all readings against the length of hole. This was regarded as very important, and was done in order to eliminate experimental errors so far as possible.

One difficulty was the levelling of the instrument before commencing a survey. The method adopted was to fix the inclinometer on a stand (provided) and to take a reading. Then the pendulum box was turned through 180°, the top or fixed part of the instrument (see Fig. 29) being clamped. The pendulum error was the sum of the readings divided by 2. Plumb-line methods of levelling were avoided as being inaccurate. It was, however, found that on a still day the instrument could be hung over the top of the hole and a vertical reading obtained in this way as a check ; and this proved to be a very accurate way of checking the pendulums at the beginning and end of a survey.

A number of checks of inclination were made against acid-bottle readings. The acid-bottle readings did not always agree, even approximately, particularly when the acid-bottle container was sent down drill-pipe.

With regard to acid-bottle surveying apparatus, when this is sent down drill-pipe, precautions have to be taken as to its position relative to the tool joints. Acid-bottle containers are often lowered on an old sand line and pulled back a calculated amount from the bottom. The pipe near the bit, having just been subjected to severe strains during drilling, the bit is pulled off bottom for the acid-bottle test. The pipe near the bit is likely to be distorted sufficiently to cause an error in the inclination read of 1 or 2°.

Fig. 22b shows a container for sending acid-bottles down a borehole, designed on the torpedo-with-extension principle. The disadvantage of the use of a long cylindrical container has been explained. For reading acid-bottles, the arrangement shown in Fig. 21 is simple and effective. The acid-bottle is placed between wooden blocks A and C, and filled with liquid to the mark on the bottle. The weight B is then moved until the mark made by the acid coincides with the surface of the liquid, and a prick is made on paper EE with the pin which is fixed to the weight. The bottle is preferably then turned through 180° between the blocks A and C, and the process repeated. The inclination is read by measuring the distance from the prick to a centre mark ; the latter having been previously made, if necessary, by the pin, after allowing the apparatus to hang freely at rest. If the results differ slightly, the correct reading will be the average of the two.

If the distance from the point of suspension in the ceiling (h, Fig. 21) to the table is 57 in., 1 in. from the centre mark would represent 1° inclination.

Figs. 23 and 24 show views of the Martienssen declinometer wagon.

Figs. 28, 29 show the interior of the wagon and the inclinometer.

Figs. 30–32 show the guides.

In conclusion : although well-surveying is now only in its infancy, it may in the near future be standard practice to survey all wells accurately. The comparative expense may be considered from the point of view that one well saved would more than pay for the most expensive outfit. The Martienssen apparatus gives results which are both accurate and certain ; and however easy and cheap a method, it is pure waste of time if it is uncertain and likely to lead to erroneous conclusions.

A question likely to be asked is : " Will the modern tendency to drill straight and vertical holes do away gradually with the necessity for accurate surveys, particularly with the necessity for expensive surveying equipments ? "

A possible answer is that :—

(1) An acid-bottle is not satisfactory for measuring angles of less than about a degree. For very small angles, more accurate methods are necessary.

(2) If deductions relating to geological and drilling data are to be made from the direction and amount of deviation, then again it is likely that accurate methods will be necessary.

(3) In the case of very deep holes, greater accuracy is desirable than in the case of shallow holes, and there is a tendency for holes to be drilled to greater depths.

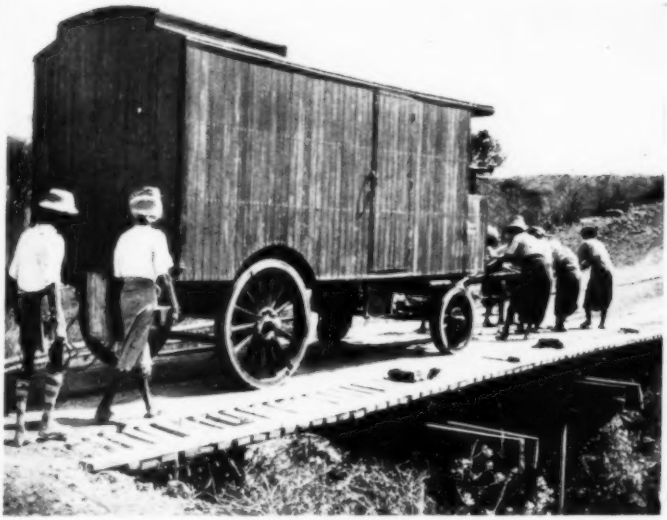


FIG. 23.

MARTIENSSEN DECLINOMETER WAGON.

FIG. 24.

BEING HAULED UPHILL. CABLE CARRIED SEPARATELY IN ORDER TO DISTRIBUTE THE LOAD.

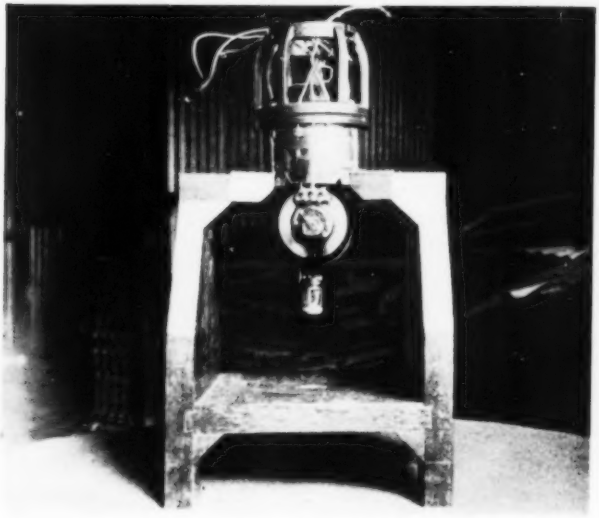


FIG. 25.
THE GYRO-COMPASS.

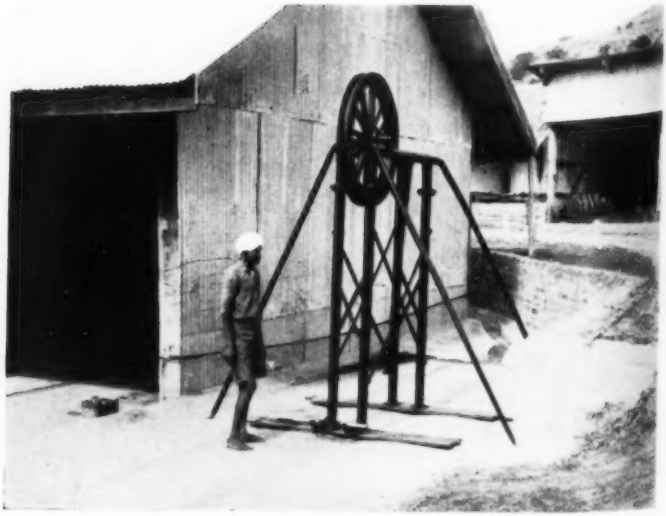


FIG. 26.
FRAMEWORK FOR USE IN RAISING AND LOWERING APPARATUS IN OIL WELLS.

FIG. 27.

CLAMPS FOR HOLDING APPARATUS RIGIDLY OVER THE OIL WELL DURING ASSEMBLY AND TIGHTENING UP OF GLANDS.

FIG. 28.

INTERIOR OF WAGON. OPERATOR TAKING A READING. NOTE BELL FOR ENABLING THE MOVEMENT OF THE GYRO-COMPASS TO BE FOLLOWED.

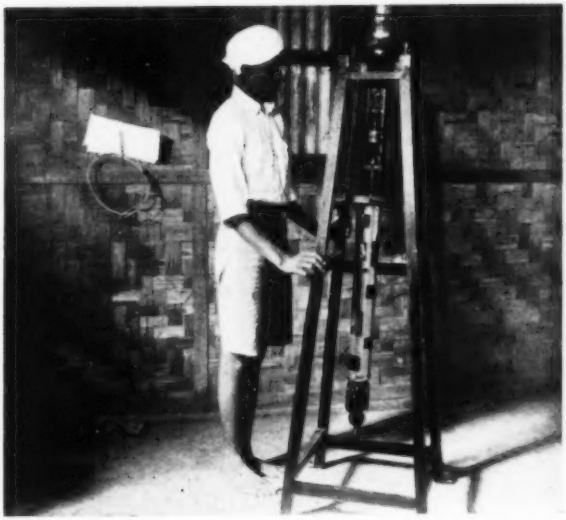


FIG. 29.
INCLINOMETER MECHANISM.

FIG. 30.
"TORPEDO-HEADS."

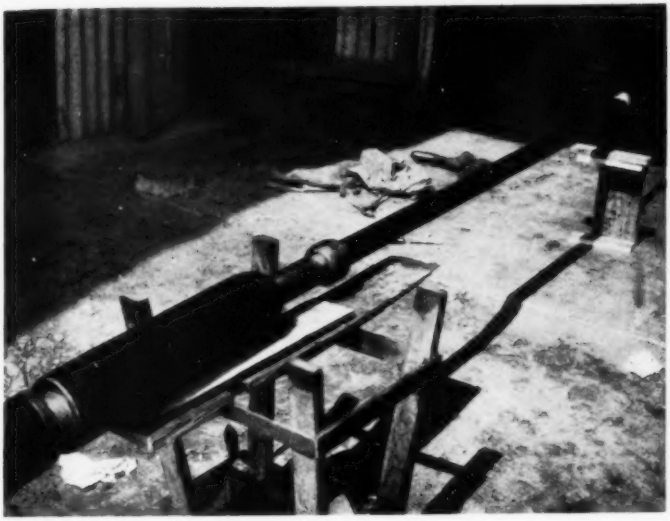


FIG. 31.

TOP TORPEDO-HEAD, SHOWING EXTENSION FOR USE IN OPEN HOLE.

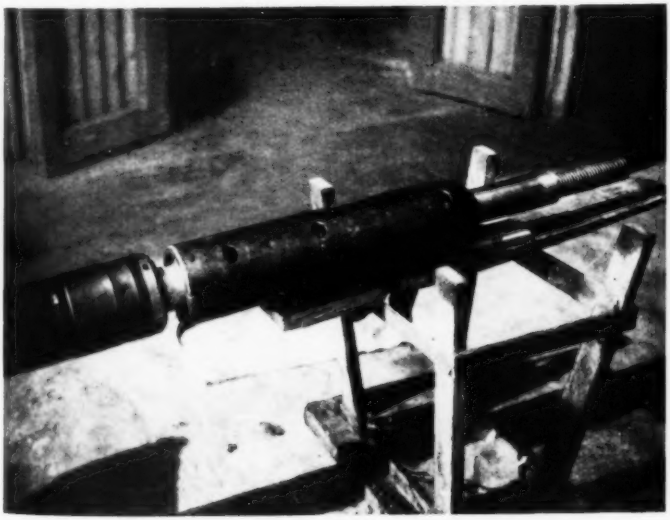


FIG. 32.

TOP TORPEDO-HEAD SHOWING SHORT EXTENSION FOR USE IN CASED HOLES.

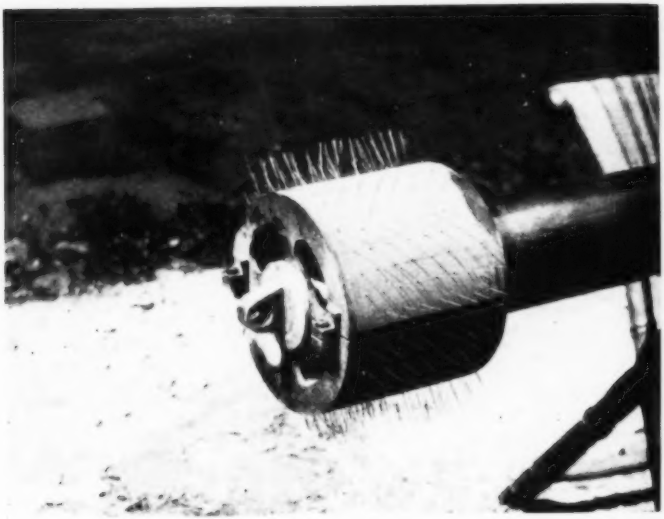


FIG. 33.

STEEL BRISTLES, TO AVOID COLLECTION OF MUD.

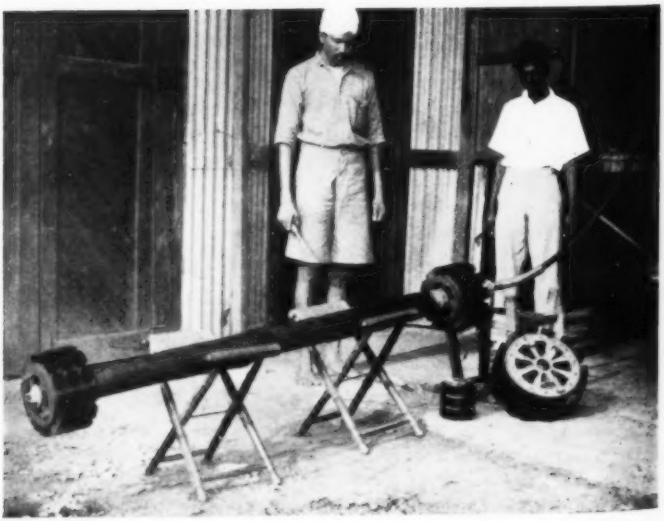


FIG. 34.

BRUSH-GUIDES AS SUPPLIED BY THE MANUFACTURERS

FIG. 35.

BRUSH-GUIDES AS SUPPLIED BY THE MANUFACTURERS.

FIG. 36.

FIN-GUIDES (NOT USED). A MODIFICATION OF THESE WAS PROPOSED FOR USE UNDER LIQUID IN HOLES WHICH WERE GASSING VIOLENTLY.

FIG. 37.

TREATING THE CABLE; THE DECLINOMETER WAGON IS SHOWN IN POSITION FOR SURVEYING AN OIL WELL. THE CABLE DRUM AND ELECTRIC MOTOR FOR RAISING AND LOWERING THE INCLINOMETER IN THE OIL WELL IS ABOARD THIS WAGON.

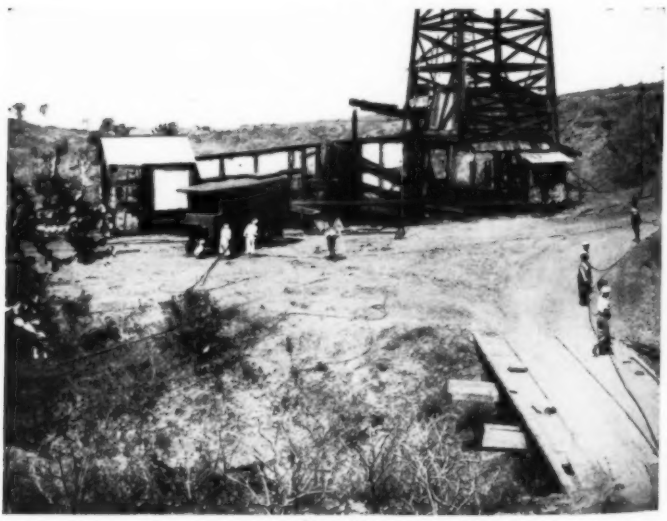


FIG. 38.

DECLINOMETER WAGON IN POSITION FOR SURVEYING OIL WELL. A LINE FROM A RIG IS BEING ATTACHED FOR HAULING IT UP A STEEP HILL.

(4) If it became necessary to drill two or more holes near to one another throughout their length for any reason, then accurate surveying would be indispensable.

Such might occur, for example, if an electrical heating unit were to be inserted in a central hole, or other methods were to be used to drive the oil from a central hole to nearby holes.

The Author wishes to express his indebtedness to Mr. Mainprise for his kindness to him whilst in Burma and for the geological details on which some of the remarks in this paper are based.

DISCUSSION.

The President said that members would agree that the paper was packed with interesting and useful information. His principal criticism referred to the order of presentation of the data rather than to the data themselves. It would have been more methodical to have dealt in the first place with inclinometers generally, then to have described the construction and mode of operation of the Martienssen inclinometer, and finally to have presented and discussed the results of surveys made with that instrument.

With regard to inclinometers in general, it was possible that the author had over-stressed the influence of well magnetic effects on methods which involved the use of the magnetic compass. It was true that the magnetic compass could not be used inside casings, but instruments involving the use of the magnetic compass had given useful results, as was proved by the very close agreement which had been found to exist between such results and the results of check surveys made with the Martienssen instrument.

He understood also that recent experience in well surveying tended to show that a very considerable degree of confidence could be placed in the results of surveys based on the use of oriented drill-pipe.

He had no doubt whatever regarding the great accuracy of the results obtainable with the Martienssen gyroscopic inclinometer. The principal drawbacks were the high cost of the instrument and its very complicated construction. The author might also have mentioned that one form of the Martienssen inclinometer, or rather of certain of its essential parts, would permit only of the recording of angles of deviation up to a maximum of about 13°, whereas in another form angles up to a maximum of about 30° could be recorded. It was very desirable that the latter form of the instrument should be employed, as many old cased wells deviated at angles greater than 13° and it was very disappointing to find that surveys could not be carried beyond a shallow or moderate depth because of the high angles of deviation of the wells.

The results of well surveys, shown on many of the figures and particularly on the contoured maps Figs. 17 and 18, agreed with the results of surveys made elsewhere with the Martienssen inclinometer, and they supported the up-dip rule which, so far as the speaker was aware, was first established in the Burma fields by the use of the Abraham inclinometer, an apparently simple but highly ingenious form of magnetic inclinometer. As the up-dip rule was well established, it should only be necessary, in a well-developed field containing many cased holes, to survey a few key wells as a guide to the direction of deviation of surrounding wells.

He would add that he was inclined to doubt the accuracy of the statements made with reference to critical angles. He thought that the evidence was not yet quite sufficient to establish such critical angles, but he desired to hear more from the author on that point. There were doubtless many present who were much better qualified than himself to criticise the paper.

Mr. A. Beeby Thompson said that he did not consider that the author, in his summary, had done justice to the paper or to his work in Burma. The author had a very difficult task to perform, taking out with him a new instrument which had not been thoroughly tested under conditions which resembled those in the oilfields, and, as he had explained, many difficulties had to be surmounted before he could get it to work satisfactorily. Doubtless many of those present would draw the conclusion from his description that the instrument described was far too complicated and delicate for ordinary oilfield work. The speaker's own impression inclined to that view, and it might fairly be argued that it was too expensive for ordinary well surveys. He had seen some of the pioneer work performed by Anderson in California, and had spent some time with him on one occasion, and he considered the results trustworthy with his oriented pipe method of surveying. The speaker very much doubted whether the detailed information obtained with these expensive instruments was going to be of compensatory value to petroleum technologists, except when dealing with cased holes.

An important point brought out very clearly in the paper was the persistence of drift in certain directions related to the dip of the strata. He thought it was now generally agreed that there was a critical angle of dip which tended to cause the bits to drift up-dip and down-dip—in this case almost universally in an up-dip direction, with a slightly clockwise deviation due to the rotation of the rotary bit. He was inclined to think that the behaviour of the bit would be different in different kinds of ground, and in this connection he had noticed that some American writers on the subject had definitely stated that they could not trace in

some fields any definite relationship of drift to dip and strike of strata. If that was the case, drift must be related in some degree to the nature of the ground in which drilling takes place. He thought that for the present it would be dangerous to assume that the same general results would be obtained in all cases, irrespective of the nature of the strata.

Many efforts had been made in recent years to keep the bit from drifting out of vertical. In Rumania some success had been achieved by incorporating a very heavy sinker or drill collar at the bottom of the drill pipe. Very naturally, a well could be kept practically vertical if the weight were reduced sufficiently to prevent more than nominal pressure on the bit. As a rule, a compromise was reached by permitting a pressure which did not cause a deviation in excess of about 3°.

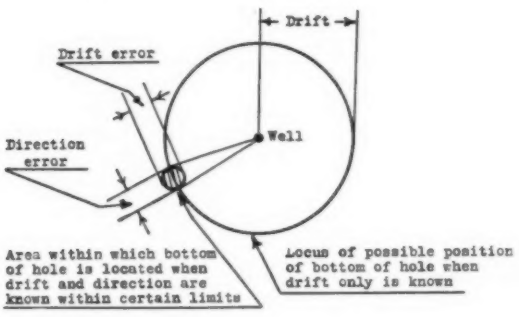
Whilst appreciating the efforts of the author to arrive at formulæ for reaching certain deductions, he very much questioned whether it was possible to express mathematically factors dependent upon so many and obscure variables.

Mr. B. J. Ellis said that he had to agree with the author as to the value of surveys of wells that had been completed before the general introduction and use of inclinometers. Of course, in wells that they were drilling they generally tried to prevent them from going crooked and took periodic readings, so that a final survey of the whole well was not necessary, although on many occasions a survey was made to check up previous readings. But he rather fell foul of the author on the question of accuracy. He did not believe that the extraordinary accuracy of the Martienssen instrument was essential. When his own people first considered the purchase of a Martienssen instrument he was much impressed with the accuracy of it and rather "downed" some of the more simple alternatives that were subsequently put into use in Burma. He had, however, to change his mind when it was pointed out that a directional survey with an instrument of quite considerable possible error reduced the possible position of the bottom of the hole from any point on the circumference of a large circle, with the surface location as centre and the drift (assumed accurate) as radius, to some point within a quite small area centred on the circumference of the drift circle and having dimensions equal to the possible total errors in drift and direction.

Extreme accuracy might be necessary for stratigraphical correlation work, but it was not necessary for ordinary development.

The Martienssen instrument was of delicate construction and costly to purchase and operate. The actual instrument which was let down the hole, not counting the cable, cost about £800, and as one naturally did not want to lose £800 down the hole the

instrument was not normally run outside the casing. Its main use was for surveying inside cased holes, where magnetic instruments could not be used, and particularly for surveying holes that had been drilled in the past and whose direction and deviation were not known, for the purpose of finding areas where in-filling wells might be profitably drilled.


Drift
Drift error
Direction error
Well
Area within which bottom of hole is located when drift and direction are known within certain limits
Locus of possible position of bottom of hole when drift only is known

The instrument was so delicate that if it was hung up in a slight breeze without its outer case, it would continue to process and would not settle down to a N. and S. position. It was not an instrument one normally wanted to use on an oilfield if one could get anything easier and simpler. The President had pointed out that methods involving the use of magnetic compasses had given results which agreed very closely with those of the Martienssen equipment. It was the present practice in Burma to take frequent directional readings with a simple instrument as drilling went on, and on occasion surveys to check up the results thus obtained had been taken with the Martienssen instrument after the casing had been put in. The two sets of readings had been found to check well with one another.

The up-dip rule had been fairly well proved, but the first well he surveyed in 1924—the first well, he believed, to be surveyed in India—went down-dip with a vengeance; it got into one particular steeply inclined stratum and stayed in it. It actually went through the bottom of another well, so that its down-dip direction was known.

The author had suggested that the rotary tended to deviate to the right of the true up-dip direction and that cable tools tended to the left. As far as rotary was concerned, the speaker believed that the direction varied according to the type of bit being used, and that, at Huntingdon Beach, where deviated drilling was

carried out to reach oil sands under the ocean, the desired direction was attained by using alternately bits of different types.

There was one point he wished to mention before sitting down, namely, that the author had a very complete knowledge of the Martienssen instrument and had made a number of valuable suggestions for detailed improvements of which his people in Burma had taken full advantage.

Mr. R. J. Ward said that, unlike the President, he was going to compliment the Author on the way he had presented the subject, namely, giving results first and the explanation afterwards. He thought it was a novel way of proceeding and one which was justified.

As to the value of the surveys made, supposing their accuracy could be relied on, he wondered whether, in view of the prevailing deep drilling, it really mattered whether the holes were straight provided tubing could pass freely and pumping had not to be relied on to secure production. The surveys would allow of the geologists to correct their contour maps and enable them also to determine the proper depth to which holes should be drilled.

In studying the plotted surveys it was very interesting to follow the course of the deviations from the straight, as those drilled by rotary appeared invariably to follow a northerly and easterly direction, whilst with cable tools the direction seemed to tend westerly and northwards. On the question of crooked holes it was of interest to recollect the method used in the past on the Russian fields—particularly as it appeared to him that modern engineering practice seemed in several ways to follow methods formerly practised on the Russian fields, but modernised and improved. When drilling in Russia, it was the custom before setting the conductor to test it for verticality by lowering a lead seal to the shoe, then lowering a plumb-bob which had been centred at the top and noting its impress on the seal. A small deviation from centre only was allowed which, if exceeded, needed withdrawing of the casing and straightening of the hole by reaming. A straight conductor, with a drilling system using guides, tended to give a reasonably straight hole, and he thought if straight holes were required this method might be enlarged to advantage. He did not consider the cost of surveying instruments excessive when compared with other costs encountered in drilling holes, and he considered that if a survey was made from time to time during the course of drilling, valuable information would be available to the geologists and corrections could be made accordingly. He therefore considered there was a decided advantage in extending the number of surveys that should be made and that it should become common practice.

Dr. J. A. L. Henderson said that he had found this paper of great interest not only as giving a description of the operation of a deep-well surveying instrument on one oilfield, but also as furnishing definite information from the results of the work in relation to the inclination, and, in particular, the direction of drift of the boreholes drilled in relatively soft strata by both percussion and rotary methods. The Author's discussion of the causes of inclination, and in particular of up-dip drift, is also a welcome addition to debates on this subject during the past thirty years.

In his own case, on one field he had been restricted to the use of the acid bottle only, in determining the deviation of the holes, because of the extremely magnetic conditions prevailing in the field and of the method of drilling called for by conditions. In conjunction with coring and geological evidence this method proved sufficient to corroborate what the Author had brought out, namely, that most of the holes, even in cable drilling, drifted up-dip, although he had found some which apparently drifted parallel to the strata and some which tended to follow the dip of the beds. The cause of deviation was very apparent. In nearly every case any marked tendency to deviation in inclined strata was caused by the contact of the bit with an extremely hard bed or a series of beds possessing a different degree of hardness or "toughness" from the prevailing type of rock traversed. Cemented sandstones, siliceous limestones, of even a few inches in thickness, "tough" limestones or "tough" bituminous shale beds, even if only moderately inclined, are found to initiate deflection, the chief cause of the trouble arising, therefore, from the nature and association of inclined beds to be traversed. In horizontal strata with similar alternations of hard and softer beds, the boreholes proved vertical down to moderate depths, a slight deviation becoming apparent below 1000 to 1400 ft., due, probably, to carelessness in drilling.

Mr. J. Romanes, in a written contribution, said: In his very interesting paper Captain Bruges, not claiming to be a geologist, has wisely steered clear as far as possible of matters geological, yet it would appear that the geological aspect must supply the answer to his final question: "Will the modern tendency to drill straight and vertical holes do away gradually with the necessity for accurate surveys, particularly with the necessity for expensive surveying equipment?" To the geologist the two vital questions are: "Where am I?" and "What am I going through?"

Mr. Ellis, in his remarks, showed that the first question can be cheaply answered within a reasonable margin of error, where the modern technique of straight drilling has not been applied, by using comparatively simple methods for determining the

approximate location of the bottom of the well. As to the question : "What am I going through ?" while there is considerable evidence to show that certain tectonic features or sharp changes of formation are shown up by a change in direction of the well, it must be admitted that the most fascinating kinks in the well surveys figured represent troubles of the drilling department. In Fig. 10 the well apparently goes through the main fault without a tremor, very different from the violent kinks induced by six twists off in Fig. 4. To detect geological changes with any certainty, only the most accurate surveys with elaborate equipment as described by the Author could be of real value. When, however, one considers on the one hand the upsetting factors introduced by different types of bit and rates of drilling, and on the other the geological records obtained from samples and more especially by coring, it would appear very questionable whether the additional geological information obtained by accurate well survey would justify the cost.

It would appear to the writer that the economic value of such surveys would be more or less proportional to the complexity of the geological structure. That is to say, in broad simple folds there would be little chance of additional geological information being picked up, and in such folds a certain latitude in bottom hole location would not matter much. On the other hand, in highly folded complex structures productive zones are narrower, straight holes are harder to drill, and any additional geological information may be of the utmost value; it is, therefore, under these conditions, that accurate borehole survey would appear to have the most scope.

Prof. Dr. O. Martienssen, in a written contribution, said : The comments concerning the course of the boreholes in comparison to the direction of the dip of the strata are very interesting, especially as in other oilfields such great regularity has not been observed. This may be due to the fact that the dip of the strata is often much greater, so that the assumed critical angle of 11° is exceeded.

As regards improvements for the guiding of the apparatus in the borehole, it is correct that the brush guides supplied were constructed in the first instance for cased holes, but in uncased holes the accuracy will somewhat suffer through unexact guiding of the brushes. However, the experience in other oilfields shows that generally the errors caused through leading by the brushes almost balance each other, also in uncased holes, so that the position of the borehole as found is inaccurate only to a very small degree.

He agreed with the comments about the cable. Rust damage on the steel core will be completely prevented by stronger tinning

of the steel wires and by choosing wires of a somewhat greater diameter. The impregnation of the covering with a compound of shellac and tar is certainly also an advantage.

In regard to the gyroscope three difficulties were described, namely, those which may be caused by the magnetism of the casing; by an uncertain contact at the contact maker of the follow-up motor, and finally by a film on the surface of the mercury. In borings up to 2000 m. depth (=6400 ft.) he had never observed troubles caused by magnetism. The troubles at the contact are also easily deceptive. They are especially caused when the contacts have been spoiled by spilled mercury. Mercury is the greatest enemy of a good contact.

On the other hand, the forming of a film on the surface of the mercury is very troublesome. It prevents the free movement of the floating system and may become the cause of quite erroneous results. It is very interesting to hear that this difficulty has been overcome by using a float made of bakelite and by the formation of hydrogen in the closed apparatus.

However, this is only a transient help, and considerable difficulties remain when a compass floating in mercury is used. For the last three years the compass with the system floating on mercury had been abandoned and the gyroscope suspended by means of an oil pressure bearing. With this bearing the gyroscope is floating upon a thin oil-film in such a way that oil is constantly pumped between the bearing pedestal and the bearing cap by means of a little pump.

This arrangement has proved exceedingly satisfactory. The orientation of the compass is perfectly exact, and the working with the apparatus has been simplified. Furthermore, the danger of the contacts being soiled by mercury has been removed. Using this compass the exactitude of the measuring has greatly increased, and so has also the speed of measuring, because the attendance has become very simple.

Capt. W. E. Bruges, in reply, said that he agreed that the magnetic compass had given very useful results, but he thought there was always an element of doubt and of slight inaccuracy in using it which would prevent the surveys from doing more than find out roughly where the bottom of the hole was situated. Such an element of inaccuracy might be enough to prevent the drillers from knowing exactly what was happening. The accuracy of surveys was, in his view, of great importance, although he admitted that this fact had been questioned. To take a parallel from another field, one might say that a tolerance of plus or minus two and a-half millionths of an inch was not likely to be required in electrical and mechanical work; but it had been proved by

a well-known manufacturing company that accuracy of this order was desirable for master-gauges for gauges for measuring interchangeable small parts so as to have mass-production without any fitting in the assembly being required. He believed that in the drilling world accurate surveying might prove of value in ways which could not be anticipated. Accurate work very often yielded unexpected results.

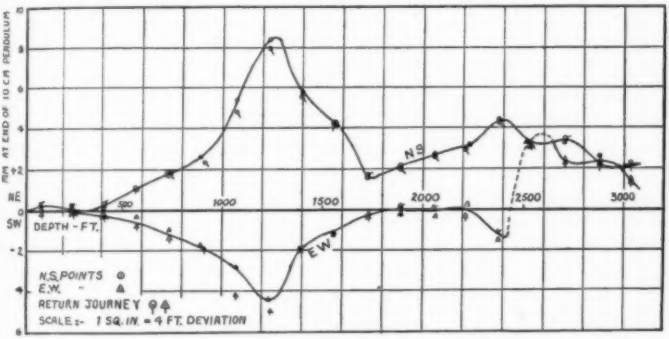


FIG. 16A

With regard to surface orientation methods, he demonstrated on the blackboard (Fig. 16A) the separate curves for North-South and East-West inclinations which could be plotted, and showed how a good deal depended upon whether these curves were similar to and in phase with one another. If they were so, then the hole was keeping in the same plane.

Any hole could be mathematically defined by two such curves. The radius of curvature of the hole could be found by measuring the angles of the tangents to the curves at any particular point. The harmonics in the two curves could be calculated, and might yield interesting results. He had found that usually there was very little spiralling, and he believed that was why surveys employing surface orientation methods were often satisfactory. If, on the other hand, there was spiralling, the position of the instrument would be some function of the spiral. One might visualise a spiral spring which was held in one hand and gradually pulled down. As it was pulled down, the wire would turn round.

With regard to down-dip deviation, Mr. Beeby Thompson had also mentioned in his book some years ago that a hole might remain in a stratum throughout its entire length.

So far as concerned deflection through hard strata, it was possible that in some cases there were some very big boulders which the

bit was trying to sidetrack. At any rate he would suggest that that was very likely to be the cause, and it would, if one were able to continue to drill, result in the hole turning back and continuing in prolongation of its original direction, perhaps so as to avoid distortion due to strain.* He would be interested to learn whether Dr. Henderson would agree with that view.

The suggestion with regard to "critical" angles is that there is likely to be an angle for a given set of conditions at which the drill will tend to overcome friction and slide down the plane (ZZ', Fig. 19) of the structure. This angle will, without doubt, depend on the formation and on the type of bit. Possibly in the case of both very hard and very soft formations the critical angle might be reduced; so that the bit might, on encountering such formations, slide and bite against the down-dip side of the hole, causing deviation in a strike direction. It has been assumed that when the dip angle is below the critical angle this sliding effect need not be considered.

Hard formation would thus cause deviation to the right, the amount being large or small in accordance with the weight on the bit. The latter will usually be comparatively small with hard formations, but larger when very soft formations are encountered. On the other hand, when a small object is sidetracked the bit would slide off, generally down-dip, bite on it and be pulled to the left.

The point made by Mr. Ward is a very interesting one—that it might often be cheaper to allow holes to deviate with a view to surveying them subsequently. The cost of the Martienssen equipment is not excessive when compared with other costs encountered in drilling boreholes. The extra time and apparatus necessary for very straight drilling might be set off against the cost of the surveying instrument. Moreover, if there is a general tendency in a particular oilfield for deviation in a known direction, allowance for deviation can be made when siting the well.

Now that gas-lift is becoming common practice, the wearing of sucker rods need not be considered to such a large extent. Hole C (Fig. 3) was a comparatively troublesome well to pump, using sucker rods.

He agreed with Prof. Martienssen that the use of mercury is better avoided, other things being equal. Those who already possess a compass which floats in mercury might, however, be interested to know that the use of a bakelite or fibre float lowers the necessary level of the mercury in the float-chamber so much that the assembled compass can be carried about reasonably quickly without mercury being spilt.

* See Fig. 4, hole E, points *i*, *j*, *k*, *l*, *m*, *n*, *o*; and compare Fig. 1, hole A, points *h*, *i*, *j*, *k*, *l*, and Fig. 9, hole L, points *l*, *m*, *n*, *o*, *p*, *q*, *r*.

The Explosion of Mixtures of Combustible Gases with Air by Nuclear Drops of Water and Other Nuclei and by X-Rays.*

Part I.—The Explosion of Gaseous Combustible Mixtures Passing Through Vitreous and Steel Combustion Tubes, by Nuclear Drops of Water.

By R. O. King, M.A.Sc. (McGill).

I. Introduction.

The nuclear theory of self-ignition as advanced by Callendar to account for the occurrence of detonation in an engine[1, 2] is based on the possession by nuclei present in a gaseous combustible mixture of chemical properties which, in the temperature conditions, lead to their simultaneous ignition and explosion before combustion is completed in the normal course of flame travel. The view that the nuclei, even if themselves incombustible, might ignite and explode the combustible mixture was not considered, but is supported by recent experiments. Thus mixtures with air of hydrogen, ethylene, carbonic oxide and acetylene have been exploded by nuclear drops of water, in suitable experimental conditions. The "conditions" depend mainly on the natures of the combustible gas and the contact surface. Experiments made with hydrogen-air mixtures passing through pyrex glass and steel combustion tubes will be described in the first instance.

II. Arrangement and Details of Apparatus.

(*a*) The arrangement of the apparatus is shown by Fig. 1. A combustion tube is supported concentrically in an electrically heated tube furnace. The gaseous mixture is passed into the tube through a ring of distributing holes at the bottom end, and the experiments being made nearly at atmospheric pressure, the top end is closed by a cover plate resting on it. When the effect of drops of water is to be tried, an injection is made through a central hole in the plate, which is covered at other times. The temperature of the central core of the gas into which injection is made is taken by a thermo-couple enclosed in a centrally held vitreosil tube.

(*b*) *Combustion Tubes and Furnaces.*—Combustion tubes and furnaces of various lengths were used, but the tubes were always of approximately $1\frac{1}{4}$ in. internal diameter. The length of the part of the tube surface which attains the maximum temperature corresponding to a particular value of the heating current is one of the factors determining surface ignition temperature. That length is proportional to the length of the furnace, but is affected

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also by the thermal conductivity of the material of the tube, the time of heating, the distribution of the resistance wire on the furnace tube, and the dimensions of the annular space between the furnace and combustion tubes. The combustion tube projected 1½ in. above the top end of the furnace, and sufficiently far below the bottom end to be cool enough for joints to be made with rubber and canvas tubing.

(*c*) *The Gaseous Mixture, Conditions and Measurement.*—The hydrogen and air, compressed in steel cylinders, were passed as required, directly into the combustion tube, and were, therefore, of corresponding dryness; mixing was effected by passing the gases through a 4-ft. length of 3/16-in. diameter rubber tube. The mixture was allowed to flow for at least 20 mins. before ignition. The time was more than required to obtain in the combustion tube when unheated a homogeneous mixture in the proportion supplied by the metering apparatus; this was confirmed by gas analysis. The direct supply was used because the explosive mixture was allowed to flow until ignition occurred; also, because changes of mixture proportion could be made rapidly. The method involved, however, the measurement of rates of gas flow as small as 2 c.c. per minute. The necessary refinements of regulation and measurement were attained by passing the gases through fine capillary tubing submerged in a constant temperature water bath and observing the pressure difference across the ends of the tubing. The rates of gas flow corresponding to observed pressure differences were obtained by the displacement of water method.

(*d*) *The Water Injecting Apparatus.*—A "Bosch" pump and nozzle, of the type used for the injection of liquid fuel into an engine cylinder, were used for the experiments. The special feature of the apparatus is that the discharge per stroke can be adjusted accurately to a very small quantity. A single injection of water into the heated gaseous mixture suffices to cause explosion if the conditions are such that the effect can be obtained. The evaporation of the injected water lowers the temperature of the gas, thus tending to prevent ignition, and it is important, therefore, to inject the minimum that can be delivered by the pump with certainty. That quantity is about 12 cu. mm., and is approximately 1/5th of the volume of the drop from the usual "dropping bottle." The quantity injected is forced through a hole nozzle 0·2 mm. in diameter by a pressure of about 70 kilos. per square centimeter; greater pressure has been used, but is not of beneficial effect. The bulk of the water injected passes through the heated gas, but fine drops surrounding the central stream persist as fog until vaporised. Water provides sufficient lubrication for the working parts of the pump, but leads to the formation of

rust and a small particle will cause the spring loaded valve plunger of the nozzle to stick open, relieving the injected water of the atomising pressure. The pump was always dismantled after use with water, cleaned with paraffin, and the essential parts submerged in the oil until required again, the oil being then removed by washing with acetone and alcohol.

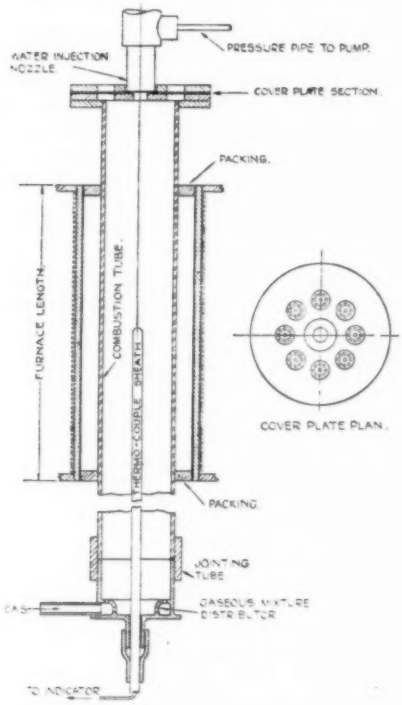

FIG. 1.

ARRANGEMENT OF FURNACE AND COMBUSTION TUBE.

(e) *Gas Temperature Measurement.*—The thermo-couples of iron-constantan and the indicator used for the experiments were calibrated and supplied by the Cambridge Instrument Company. Ignition temperatures were observed with the thermo-electric junction placed at the position of maximum temperature on the vertical axis of the combustion tube. The position is defined

somewhat sharply even when the furnace is 12 in. long, and was found by experiment for the tubes used. The vitreosil sheath of the couple is in line with the direction of injection and intercepts part of the water spray. The spray is well dispersed when it reaches the sheath, which is of small diameter ($\frac{1}{4}$ in.), and allows the greater part of the spray to remain in or pass through the gaseous mixture. The spray cools the sheath slightly, the effect being just noticeable on the temperature indicator if relatively large injections are tried. The striking of part of the spray on the sheath is not a factor leading to ignition of the gaseous mixture. This was confirmed by withdrawing the thermo-couple and sheath just before injection and by experiments made with the thermo-couple threaded through a small vitreosil tube held near the wall of the combustion tube to avoid the impact of the injected water. The temperature measured close to the side wall is about 4° higher than that indicated at the same time by a second thermo-couple at a position on the vertical axis, at the same level; the difference is of the order of accuracy of the method of measurement.

(*f*) *The Cover Plate.*—The design of the cover plate is shown at A, Fig. 1. The plate was made up of metal and uralite discs bolted together. The small holes for the exit of the gaseous mixture were made in the metal. When the exit area was too small, hydrogen-air escaped in preference to steam which remained to dilute the mixture in the tube, with the effect of raising ignition temperature. On the other hand, if the exit area were too large, convection currents induced atmospheric air to enter the tube. Satisfactory exit conditions were obtained when the total area was about double that of the holes in the mixture distributor at the bottom end of the combustion tube.

III. Preliminary Experiments Made Using Vitreous Combustion Tubes.

Recorded ignition temperatures of gaseous mixtures obtained by heating externally the combustion tube carrying the mixtures have been obtained, so far as known, when the tubes were fixed horizontally, the position being selected to suit the means of heating available to earlier observers or to promote uniformity of temperature over the length of the tube. The gaseous mixture flowing upward in a combustion tube fixed in a vertical position necessarily comprises a central stream surrounded by a boundary layer tending to become fixed as an adsorbed layer on the surface of the containing wall. The ignition and explosion of the central stream of gas by nuclear drops of water occurs at relatively high temperatures only. The possibility of observing the phenomenon depends, therefore, on ensuring that the boundary layer does not

ignite at lower temperatures, or that flameless surface combustion is not so rapid as to deplete the central core of electrolytic gas sufficiently to render it non-inflammable.

Preliminary experiments were made using combustion tubes of pyrex glass, hard glass, clear and opaque vitreosil, fitted in furnaces 6, 12 and 16 in. long. All of the materials altered in nature with continued use at temperatures approaching 700°. The effect led to changes of surface activity indicated by corresponding changes of self-ignition temperature. A self-ignition temperature of 483°, for example, was obtained on passing a 60 per cent. hydrogen-air mixture through an opaque vitreosil tube in the 16-in. furnace, whereas ignition was not obtained until the temperature reached 628°, when the mixture passed through a pyrex tube in the 6-in. furnace. The experiments showed that if vitreous combustion tubes are used, the conditions required to demonstrate the igniting effect of nuclear drops of water are obtained most readily when a new pyrex glass tube is used in the shortest practicable length of furnace.

IV. Experiments with Pyrex Combustion Tube No. 1 6-in. Furnace.

The pyrex tube, 11 in. total length, when fixed in the electric furnace, as shown by Fig. 1, was not strained in any way, and the internal pressure being little above atmosphere the softening of the glass at temperatures of about 700° did not lead to distortion. Before repeating an ignition temperature the steam remaining from a previous explosion was swept from the tube by the nearly dry air from the storage cylinder, while the temperature was maintained at over 500°. The furnace was then allowed to cool until the thermo-couple indicated 500°, when a hydrogen-air mixture of measured proportions was passed in at the rate of 100 c.c. per min., while the temperature fell to 300°, and was then raised until the mixture exploded. Self-ignition temperatures so obtained for mixtures decreasing in hydrogen content are given in the order observed in Table I. below.

The ignition temperatures given in Table I. comprise all of those observed. Ignition and explosion could not be obtained when the mixture supplied contained more than 70 per cent. or less than 12½ per cent. of hydrogen. The consistency of the results is due to arranging that the boundary layer moves over the shortest practicable length of heated pyrex glass surface to reach ignition temperature.

Experiments to determine the temperatures of ignition of the central stream of the gas by nuclear drops of water were made following the heating and filling procedure already described.

TABLE I.

Self-Ignition Temperatures of Hydrogen-Air Mixtures Passing Through a 1¼-in. Diameter Pyrex Glass Tube at the Rate of 100 c.c. per Min.

Percentage of H in mixture.	Self-ignition temperatures.		
70	652°	648°	651°
60	628°	630°	628°
50	592°	592°	590°
40	585°	585°	586°
30	578°	578°	578°
20	575°	574°	575°
15	580°	579°	580°
12½	586°	—	—

The first injection of water into a particular mixture was made at a temperature lower than that probably required for ignition and explosion. A failure to observe an explosion was followed by further injections made generally after successive 5° rises of temperature. An endeavour was made to restrict the number of successive injections, because the mixture was diluted by the steam formed. The small quantity of water found at the bottom end of the tube after several injections was cleared away before beginning a new set. Temperatures of injection into mixtures varying in hydrogen content from 90 to 50 per cent. are given in Table II. The temperatures at which explosions were observed are underlined :—

TABLE II.

Nuclear Ignition Temperatures of Hydrogen-Air Mixtures Passing Through a 1¼-in. Diameter Pyrex Glass Combustion Tube at the Rate of 100 c.c. per Min.

Percentage of H in mixture.	Nuclear ignition temperature (underlined).		
70	590°	600°	—
80	600°	605°	610°
90	620°	625°	634°
60	590°	—	—
55	580°	585°	—
60	580°	585°	—
50	580°	585°	590°
50	580°	580°	585°
70	590°	595°	—

The average ignition temperatures of Table I. and the minimum values of Table II. are shown by Fig. 2, graphs (1) and (2) respectively, and illustrate unusually consistent explosion temperatures. Nuclear drop ignition could not be distinguished from self-ignition in mixtures containing less than 50 per cent. of hydrogen, but it will be noticed that the effect was observed in extremely rich mixtures. The explosions were then very feeble, and on fitting a

small window in the cover plate, it could be seen that the flame following injection was a small patch which did not spread throughout the mixture. It was possible in the circumstances to repeat the ignition effect by successive injections of water at short intervals.

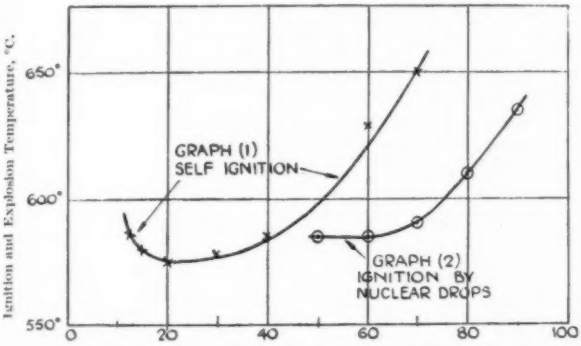

FIG. 2.

SELF AND NUCLEAR DROP IGNITION. PYREX COMBUSTION TUBE NO. 1. 6-INCH FURNACE.

On completion of the experiments described, similar effects were obtained with mixtures of ethylene and air, but with continued use of the pyrex tube, boundary layer ignition became erratic and tended to mask the possible effect of small drops of water to ignite the central stream. It appeared that the central stream of gas might be protected from self-ignition, and the igniting effect of drops of water then demonstrated with greater ease if the boundary layer were of inert gas. The combustion tube arrangements were altered accordingly in an endeavour to provide an annular stream of nitrogen with hydrogen-air as the central core. Various precautions were taken to prevent mixing of the gases, but success was not attained.

V. EXPERIMENTS WITH STEEL COMBUSTION TUBES.

There seemed to be a possibility that a boundary layer containing sufficient steam to be non-inflammable might be obtained on a surface of iron or steel in a state of active oxidation, and experiments were begun with steel combustion tubes. Ignition temperatures of combustible mixtures in contact with hot metal surfaces are of interest in engine practice, and the tubes selected for experiments were a variety of chrome nickel steel suitable for exhaust

valves required to operate while red hot. The steel, according to the makers, contained substances other than iron in the following proportions : C 0·12 per cent. ; Si 0·6 per cent. ; Mn 0·3 per cent.; Ni 8·0 per cent. ; Cr 18·0 per cent. ; W 0·6 per cent. The steel tube, $1\frac{1}{4}$ in. internal diameter, was fitted in the 6-in. furnace as shown by Fig. 1, but was made 3 in. longer than the pyrex tube in order that the lower part should not become hot enough to damage the end connection. Ignition temperatures were observed following the procedure adopted when using the pyrex tube. The experimental results can be described most conveniently in connection with a series of graphs showing the relation between ignition temperature and mixture strength.

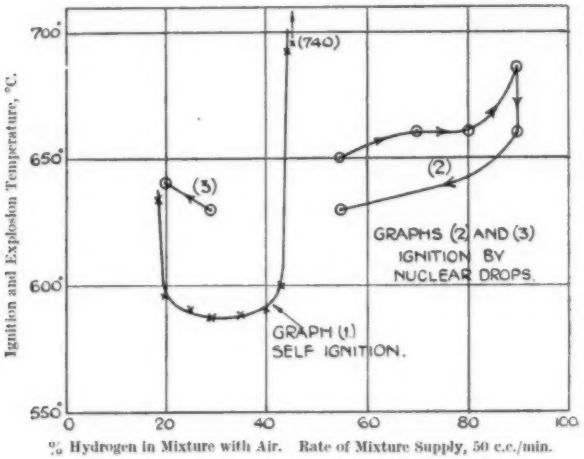

FIG. 3.

SELF AND NUCLEAR DROP IGNITION. STEEL COMBUSTION TUBE. 6-INCH FURNACE.

The self-ignition temperatures observed when the tube was in new condition and the gaseous mixture passed into it at the rate of 50 c.c. per min., are shown by graph (1), Fig. 3. The minimum of 586° obtained when the mixture supplied contained hydrogen in nearly combining proportions is not an unusual value. The range of inflammability, namely 18 per cent. to 45 per cent., of hydrogen in the mixture supplied is, however, remarkably narrow.

Water was injected into rich mixtures, beyond the limit of inflammability by self-ignition. An injection into a 55 per cent.

hydrogen mixture at 580° was followed by others as the temperature rose, and a sharp explosion occurred at 650°. The nuclear ignition temperatures shown by graph (2) were then obtained in a similar manner and in the order indicated by the arrows. The nuclear ignition temperature of the 90 per cent. hydrogen mixture was found to be 685°, but on repeating the experiment a little later an explosion was obtained by injection at 660°. The apparatus then stood idle overnight, and the next day an explosion was obtained on injecting into a 55 per cent. hydrogen mixture at

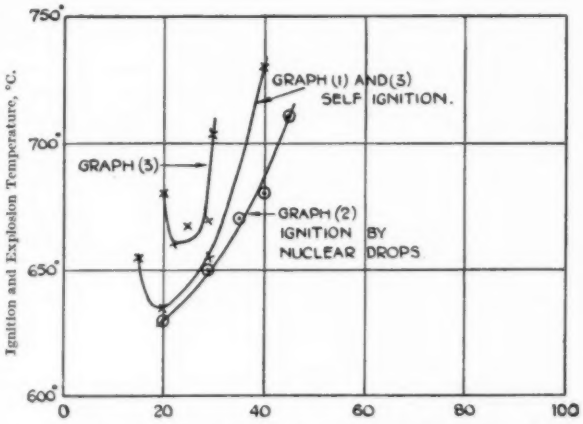

FIG. 4.

SELF AND NUCLEAR DROP IGNITION. STEEL COMBUSTION TUBE. 6-INCH FURNACE.

630°. The experiments were continued with mixtures of combining proportions and weaker. The two points on graph (3) were obtained on injection of water at temperatures which, according to graph (1), were well above those required for self-ignition. An extraordinary change had, therefore, occurred in the factors determining self-ignition. This was verified by adjusting the heating current to maintain the temperature at 700°, and then slowly altering the rates of flow of the gases to vary the proportion of hydrogen in the mixture from 0 to 100 per cent. An explosion was not obtained and the injection of water was without effect.

The desired boundary layer, made non-inflammable by a high content of steam, had evidently been obtained coincident with

oxidation and reduction activity on the surface of the "stainless" steel. The velocity of the steam forming reaction was, however, greater than expected, and flameless combustion on the surface reduced the combustible content of the mixture, which was supplied at the rate of 50 c.c. per min., to such an extent that the central stream itself became non-inflammable. An increase in the rate of mixture was required, therefore, to obtain a combustible mixture in the central stream.

The rate of mixture supply was increased to 150 c.c. per min., and the graphs of Fig. 4 were obtained. Graphs (1) and (3) give self-ignition temperatures observed respectively before and after the injections of water made to obtain graph (2). The rise of self-ignition temperatures and the contraction of the range of inflammability during the period show that surface activity was increasing so rapidly that the central stream was again becoming incombustible.

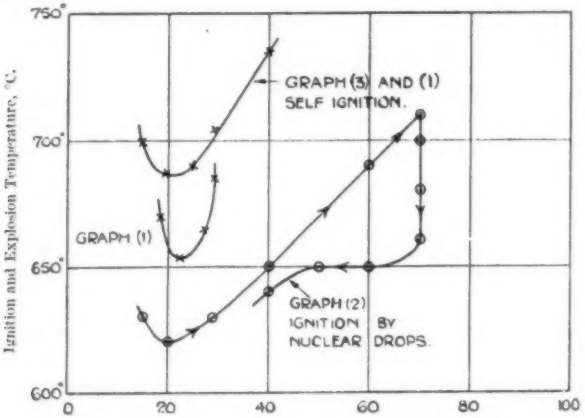

FIG. 5.

SELF AND NUCLEAR DROP IGNITION. STEEL COMBUSTION TUBE. 6-INCH FURNACE.

The rate of mixture supply was further increased to 200 c.c. per minute, and the graphs of Fig. 5 were obtained. Graphs (1) and (3) of the figures show, as before, self-ignition temperatures observed before and after the injections of water required to obtain the nuclear ignition temperatures of graph (2). Graphs (1) and (3) showing a rise of self-ignition temperature over the period indicate that the rate of steam formation on the active surface had increased

during the corresponding interval, due no doubt in part to the stimulation of oxidation by the water injected to obtain graph (2). Graph (2) giving nuclear ignition temperatures observed in the order shown by the arrows, indicates also that surface state was changing continuously during the experiment. This factor accounts for changes in self and nuclear ignition temperatures and range of inflammability.

The condition brought about by the reactions proceeding on surface is shown by the photograph taken after splitting the tube on completion of the experiments described last. Red and brown oxides predominate near the relatively cool ends. The middle or hottest part shows, however, a broad thin band of red if viewed obliquely, but not apparent in the photograph. The photograph was taken by Messrs. Ilford Ltd., using infra-red light, which accounts for the reds and browns showing white. The reddish-brown band at the top end is very much over-emphasised by glare. The definite demarkation of the bands of colour on the surface of the combustion tube shows the orderly manner of the reactions occurring as the gaseous mixture flows upward. Explosion temperatures, in the circumstances, tend to fall on a smooth curve. A similar effect is not obtained when the combustion tube is used in a horizontal position.

VI. Interpretation of the Experimental Results.

The ignition effect described cannot be due to the action of part of the waterspray, if striking the heated wall of the combustion tube, to bring a small portion of combustible mixture into intimate contact with it, because on injecting the water as a cone-shaped spray, divergent nozzles of 15° and 30° being tried, ignition was not obtained. The possibility that disturbance of the gaseous mixture by the sudden conversion of part of the injected water, into steam, might lead to ignition, has been investigated. The quantity of water injected is usually about 12 cubic millimetres and part only is converted into steam; assuming complete conversion at 650°, a volume of 55 c.c. of steam would be formed suddenly in a combustion tube of a volume of 280 c.c. (14 in. long steel tube). The sudden conversion into steam of the *total* quantity of water discharged by a stroke of the pump was effected by injecting into a "flash" boiler fixed axially in the upper part of the combustion tube, as shown by Fig. 7. The boiler extended into the furnace nearly to the position of maximum temperature and was provided with a re-entrant steam nozzle to ensure that the steam blown into the hydrogen-air mixture was free from entrained water. Experiments

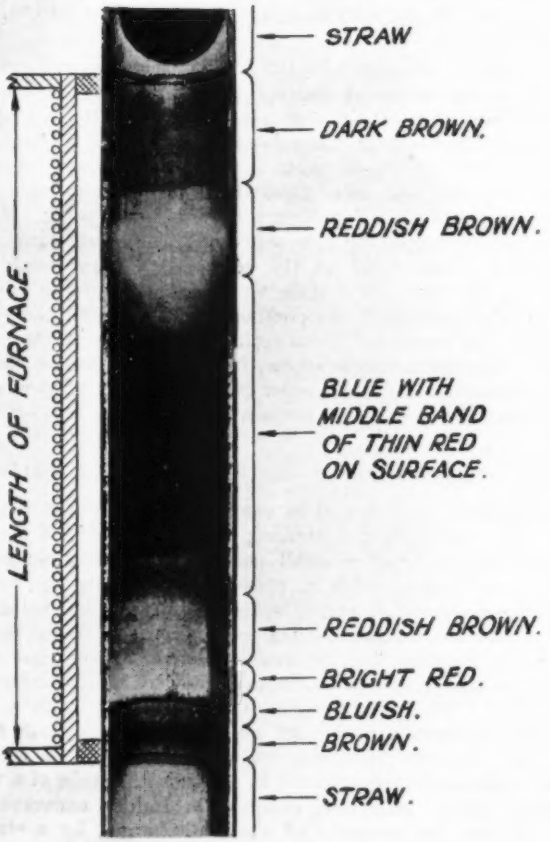

FIG. 6.

PHOTOGRAPH OF INSIDE SURFACE OF STEEL COMBUSTION TUBE TAKEN AFTER USE AND SHOWING SHARP DEMARCATION OF COLOUR BANDS.

were made with a mixture containing H_2 and air in equal proportion to obtain conditions in which, depending on the rate of mixture flow, explosion would occur either on heating the mixture or on

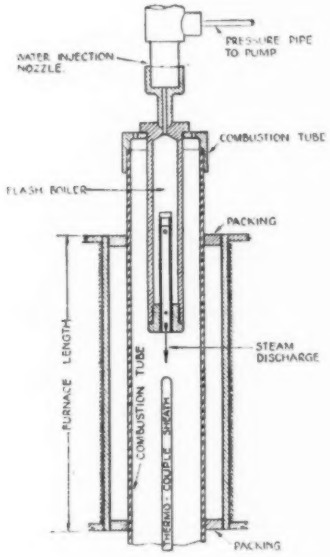

FIG. 7.

ARRANGEMENT OF FLASH BOILER FOR INJECTING STEAM INTO THE COMBUSTION TUBE.

injecting water into it. The nuclear drop and self-ignition temperatures at rates of mixture flow of 150, 200 and 300 c.c. per minute having been obtained, as shown by the graphs, Fig. 8, the pump bozzle was connected to the flash boiler and the discharged water passed into the mixture as a puff of steam. The temperatures at which steam injections were made are marked by the letter S, and when ignition occurred, the corresponding temperature is marked by the letter enclosed in a circle. When the rate of mixture flow was 300 c.c. per minute, the temperature of self-ignition was not lowered by the puff of steam, but the injection of water lowered it by 30°. When the rate of mixture

flow was greatly diminished, self-ignition temperatures rose rapidly, as would be expected, and the disturbance due to a puff of steam becoming relatively greater, ignition temperature observed on the injection of steam diminished, but remained 50° above the temperature of ignition by drops of water. The experiments show that the explosion observed when water is injected into the treated gaseous mixture cannot be due to the action of the accompanying steam and indicate also that the effect cannot be attributed to dissociation. However, in order to verify that the

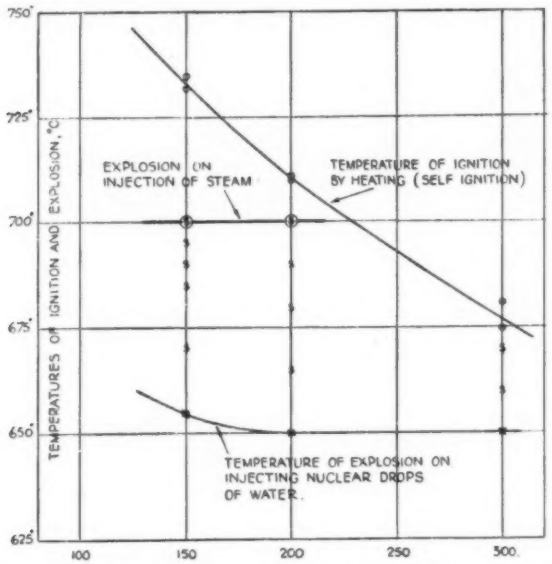

FIG. 8.

THE EFFECT OF SUDDENLY CONVERTING THE INJECTED WATER INTO STEAM. THE LETTER S INDICATES THE TEMPERATURE AT WHICH PUFFS OF STEAM WERE INJECTED.

igniting effect is purely physical, the experiment was tried of passing finely divided particles of refractory material through the gaseous mixture in the conditions selected for steam injection. The refractory nuclei were found to be more effective to ignite

and explode the gaseous mixture than the nuclear drops of water. The experiments may be of some interest in respect of dust explosions and will be described separately.

The explosion of gaseous combustible mixtures by the means described shows that active centres of ignition need not be chemically active. Callendar's nuclear theory of ignition,[1, 2] advanced to explain the cause of detonation in the engine, is therefore based unnecessarily on the possession by the nuclei of an ignition temperature lower than that of the surrounding gaseous mixture. An ignition temperature cannot be possessed by drops of water or by particles of refractory material. Nuclei of either sort become electrified in the conditions of the experiments described, and consequently the observed igniting effect may be electrical in character. The electrification of drops of water by splashing was observed by Lenard,[3] and the nature of the electrification obtained when water is sprayed into a current of air has been investigated by several experimenters : see Nolan[4] and a memoir by J. J. Rey, "Sur l'Ionisation de l'Air par les Chutes d'Eau," published by Gauthier-Vielars, 1912. The possibility that chemical action in a gaseous combustible mixture might be promoted by drops of water was suggested by J. J. Thomson[5] forty years ago, and the view that chemical action is electrolytic in character was urged by H. E. Armstrong even earlier. The view that the ignition and explosion of combustible gaseous mixtures by drops of water is electrical in character is, moreover, supported by the work of Finch and Cowen,[6] showing that the ignition of such mixtures in *electric discharges* follows "the attainment in some portion of the gas traversed by the discharge, of a certain definite concentration of suitable ions or *electrically charged particles*."

Acknowledgments.

The experiments, other than those required initially to demonstrate the igniting effect of drops of water, were made with the help of Messrs. John Rankine and George Mole.

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[1] Callendar, King and Sims, Aero. Res. Ctte. Reports and Memoranda, No. 1013 ; also *Engineering*, April 9th et seq., 1926.

[2] Callendar, King, Mardles, Stern and Fowler, Aero. Res. Ctte. Reports and Memoranda, No. 1062 ; also *Engineering*, Feb. 4th et seq., 1927.

[3] *Wied. Ann.*, XLVI. 1892, 584.

[4] *Proc. Roy. Soc. A.*, 1914, **90**.

[5] *Phil. Mag.*, 1893, **36**, 320.

[6] *Proc. Roy. Soc. A.*, 1927, **116**.

PART II.—THE EXPLOSION OF HYDROGEN-AIR MIXTURES BY X-RAYS.

By R. O. KING, M.A., Sc. (McGill).

I. INTRODUCTION.

The experiments described in Part I. indicate that ignition leading to the explosion of hydrogen-air mixtures, in the absence of nuclei in the gaseous mixture, is initiated in the layer of gas adjacent to the heated surface of the combustion tube. The experiments were continued in the expectation that the state of electrification of the surface layer of gas might be a factor affecting the temperature of ignition.

II. EXPERIMENTAL APPARATUS.

The experiments were made, using the arrangement of combustion tube and furnace described in Part I. The water-injecting nozzle was replaced by an X-ray tube and the plate covering the top end of the combustion tube by one fitted with a thin disc of aluminium. The photograph, Fig. 1, shows the arrangement of electric furnace, vertically supported combustion tube and X-ray tube. The "Metallix" fan-cooled X-ray tube was supplied on loan by Messrs. Philips Industrial Ltd., and was excited when required by 55 kV (peek) derived from a special transformer working off a 220-volt A.C. supply. The distance of the hottest part of the combustion tube from the centre of the X-ray tube was about 9 in., and the normal output of X-rays was estimated by Messrs. Philips at 24 "r" units per minute at the distance mentioned. The "r" unit is defined as: "The quantity of X-radiation which, when the secondary electrons are fully utilised and the wall effect of the combustion tube is avoided, produces in 1 c.c. of air at 0° C. and 760 mm. such a degree of conductivity that one electrostatic unit of charge is measured at saturation current." The X-radiation may be taken to be uniform over a horizontal section of the combustion tube, but the concentration of ions at the position of maximum temperature would depend on the mixture strength, rate of mixture flow which increased with rise of temperature and the variation of X-radiation along the axis of the tube. The concentration of ions in the boundary layer would in any event be greater than that in the central stream of gas, because of the secondary ionisation due to the X-rays striking the heated wall.

III. PRELIMINARY EXPERIMENTS, STEEL COMBUSTION TUBE.

The stainless steel tube used for the experiments was of the variety described in Part I., the inner surface being descaled and in new condition. The gaseous mixture was at first supplied

at the rate of 50 c.c. per minute, as in the earlier experiments, but on account of oxidation of the tube surface, it soon became necessary to raise the rate of gas flow to 150 c.c. per minute, in order to keep the self-ignition temperature within the range of

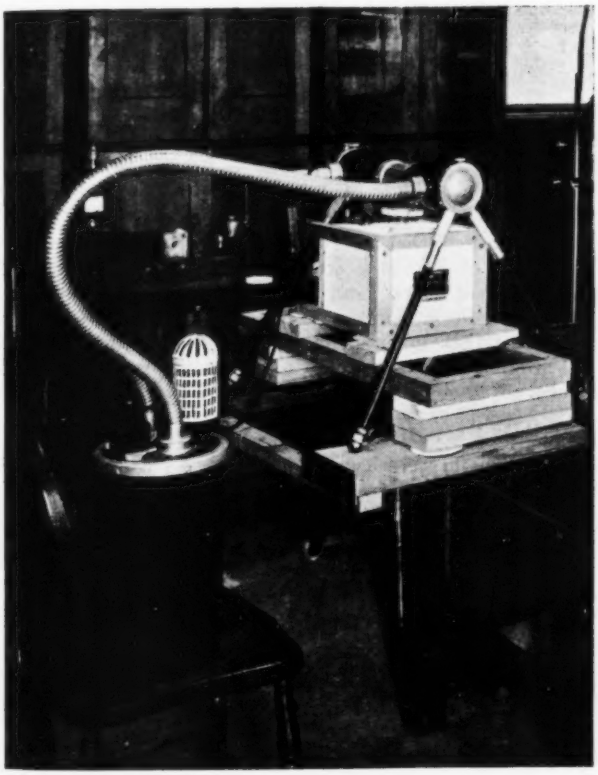


FIG. 1.
ARRANGEMENT OF FURNACE, COMBUSTION TUBE AND X-RAY TUBE.

observation, that is, below 750° C., the maximum of the temperature indicator scale. Ignition temperatures with and without X-rays were then taken alternately in an endeavour to obtain mean values compensating the effect of change of surface oxidation

state occurring during the experiment. Three sets of ignition temperatures are given in Table I. below :—

TABLE I.

Ignition Temperatures, Hydrogen-Air Mixtures passing through a Stainless Steel Combustion Tube, with and without X-Rays. Rate of Mixture Flow, 150 c.c. per Minute.

Observation number.	Mixture proportion.	Self-ignition temperature.	Ignition temp. with X-rays.
(1)	25 per cent. H_2	625°	
(2)	„ „		620°
(3)	„ „	623°	
(4)	30 per cent. H_2	664°	
(5)	„ „		650°
(6)	„ „	656°	
(7)	35 per cent. H_2	695°	
(8)	„ „		695°
(9)	„ „	692°	

It will be noted that the diminution of ignition temperature by the action of X-rays is scarcely sufficient to be accepted as evidence of a real effect. It is significant, however, that in every case the self-ignition temperature taken after the use of X-rays is lower than that taken before, although the general tendency is for self-ignition temperatures to rise with time of use of the steel tube.

IV. X-RAY EXPERIMENTS, PYREX COMBUSTION TUBE NO. 2.

The experiments were begun with a new Pyrex tube, similar to tube No. 1 of the earlier experiments, for which self and nuclear drops of water ignition temperatures were available. Preliminary trials were made, using the rich mixtures for which self-ignition is obtained at relatively high temperatures or not at all. The ignition temperatures observed are given in the table below :—

TABLE II.

Preliminary Experiments, using a Pyrex Tube and showing Ignition of rich H_2-Air Mixtures by X-Rays. Rate of Mixture Supply 100 *c.c. per Minute.*

Percentage H in air.	Self-ignition temperature.	X-ray ignition temperature.	Time of exposure to X-rays.
29	572°	Not taken	—
70	656°	„	—
60	628°	„	—
75	None	608°	—
„	„	615°	—
„	„	617°	6 mins.
„	„	626°	8 mins. 20 secs.
„	„	617°	6 mins. 45 secs.
70	656° as above	611°	—
„	„	618°	9 mins. 35 secs.

Referring to Table II., it is of interest that mixtures containing 75 per cent. of hydrogen were ignitable by X-rays in view of the

failure to obtain self-ignition of similar mixtures by heating alone. The ignitions obtained by X-rays led, however, to very feeble explosions, similar to those observed when drops of water were injected into still richer mixtures. The explosions obtained when the 70 per cent. hydrogen mixtures were exposed to X-rays were quite sharp and the ignition temperatures of 611° and 618° decisively lower than the corresponding self-ignition temperature of 656° obtained by heating.

After obtaining the experimental results of Table II., a series of hydrogen-air mixtures of decreasing proportions of hydrogen were exposed to X-rays, while the temperature was raised until ignition occurred. Exposure to X-rays was begun at 425°, while the furnace was cooling, and continued while the temperature fell to 400°, and was raised by reheating until ignition occurred. The method was adopted to secure a relatively long exposure of the moving mixture to the radiation. The long exposures were given as a precautionary measure; ignition, when possible, seemed to be promoted as effectively by a few seconds' exposure as by one of as many minutes. The ignition temperatures observed are given in Table III. below :—

TABLE III.

X-Ray Ignition Temperatures, H_2-Air Mixtures in Pyrex Combustion Tube No. 2. Rate of Mixture Supply 100 *c.c. per Minute.*

Percentage H_2 in air.	X-ray ignition temperature.
70	582°
75	618°
80	614°
65	588°
60	580°
50	580°
45	578°
40	577°
35	573°
30	580°
20	589°
15	Temperature raised to 700° without ignition.

The X-ray ignition temperatures of Table III. are shown by graph (2), Fig. 2, and for comparison, the self-ignition temperatures obtained previously with the similar Pyrex tube No. 1 are given by graph (1). The three self-ignition temperature observations of Table II., taken with the No. 2 Pyrex tube, are plotted, graph (3), to show that the surfaces of both tubes, when new, were of similar igniting effect. The ignition temperatures of Table III. were observed in the order given; the final experiment being an unsuccessful attempt to obtain an ignition temperature for a 15 per cent. hydrogen mixture by raising the Pyrex tube to above 700°.

X-ray ignition could not be obtained afterwards at any mixture strength. The effect was not recovered on increasing the rate of mixture flow, on giving longer explosure to X-rays, on using a more powerful X-ray tube, or on passing the gases through water columns before admission to the combustion tube.

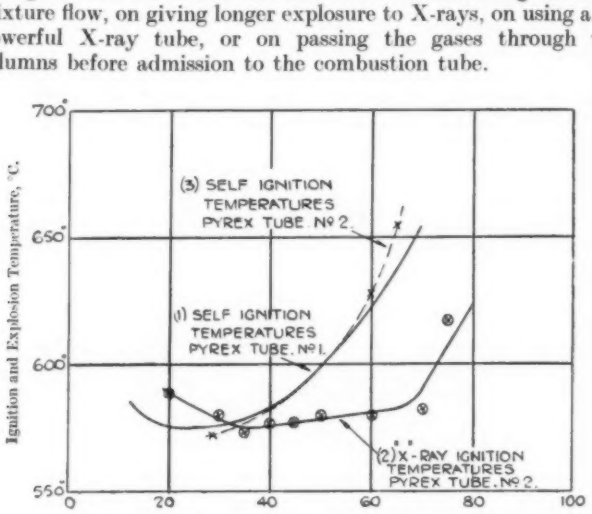


FIG. 2.

X-RAY IGNITION TEMPERATURES. PYREX COMBUSTION TUBE, NO. 2. 6-INCH FURNACE.

V. EXPERIMENTS MADE TO EXPLAIN THE DISAPPEARANCE OF THE X-RAY IGNITING EFFECT.

The experiments described in IV. were begun with a new Pyrex tube and with mixtures containing over 70 per cent. of hydrogen. The rich mixtures were used because it was known from previous experiments that they could not be ignited and exploded by heating only. Explosion by X-rays was obtained on the first attempt, and the effect could always be repeated in the conditions described, but not after exposure of the Pyrex tube to mixtures containing excess oxygen. It was decided, therefore, to make a set of experiments beginning with a new Pyrex tube and rich mixtures exposed to X-radiation, but not raising the temperature higher than required for ignition. until after successive reductions of the hydrogen content, the mixture contained excess oxygen. The experimental results are given graphically by Fig. 3, the observations being numbered in the order taken, and it will be seen that beginning with observation No. 1, ignition is, on the

basis of previous experiments, due to the action of X-rays. After taking observation No. 7, the proportion of hydrogen was further reduced to 20 per cent. to obtain oxygen in excess, and the temperature raised to 700°, and observations 7 to 12 taken an hour later. It will be seen that explosions occurred at self-ignition temperatures; that is, X-rays were without effect. This was verified by repeating observations 10, 11, 12 with and without X-radiation.

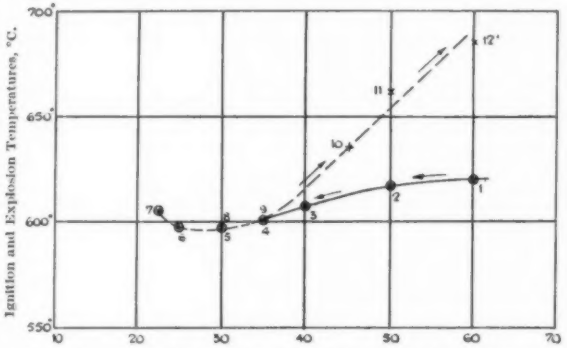


FIG. 3.

IGNITION EXPERIMENTS SHOWING DISAPPEARANCE OF X-RAY EFFECT AFTER EXPOSURE OF SURFACES TO OXIDISING CONDITIONS. PYREX COMBUSTION TUBE NO. 3. 6-INCH FURNACE.

VI. INTERPRETATION OF THE EXPERIMENTAL RESULTS.

The experiments show that when hydrogen-air mixtures are passed through a heated Pyrex tube, conditions can be obtained in which the layer of gas adjacent to the heated surface is ignited by the electrification due to the action of X-rays striking the surface. The igniting effect confirms the prediction by J. J. Thomson,[1] "that the action of surfaces (in gaseous explosion) might ultimately be found to depend on the fact that they formed a support for layers of electrified gas in which chemical change proceeded with high velocity."

The conditions in which the X-ray igniting effect is obtained and then disappears indicate that ignition, when obtained, occurs in the boundary layer adjacent to and moving slowly over the heated surface. When the heated surface is oxidised so that

[1] Contribution to Gaseous Combustion Discussion, B.A., 1910, p. 501.

reducing and oxidising actions can proceed simultaneously, two effects are obtained, namely: (1) electrification increases and (2) rate of steam formation increases. The first effect promotes ignition of the adjacent boundary layer; the second delays ignition by diluting it with steam. Ignition by X-rays depends, therefore, on increasing the electrification of the boundary layer *before* it is rendered relatively non-inflammable by dilution with steam. Thus, when a steel combustion tube is used, the surface becomes oxidised almost immediately, steam is formed with great rapidity and dilution of the boundary layer tends to inhibit ignition by the electrification accompanying the surface actions or by that produced by X-rays.

The steam-forming surface action is relatively less rapid when a new Pyrex glass surface is exposed to a gaseous mixture containing excess hydrogen. An increase of electrification by X-rays will then give rise to ignition of the boundary layer at a lower temperature than that at which it is induced by the heated surface only.

Acknowledgments.

The experiments were made with the assistance of Mr. John Rankine and Messrs Philips Industrial Ltd.

Part III.—The Explosion of Hydrogen-Air Mixtures by Stone Dust.

By R. O. King, M.A.Sc. (McGill), and George Mole, B.Sc., A.R.C.S., D.I.C.

Introduction.

The explosion of hydrogen-air mixtures by nuclear drops of water was described in Part I. The experiments indicated that the explosion of a gaseous combustible mixture could be induced by nuclei, not in themselves combustible. It was mentioned in support of that conclusion, that finely-divided refractory material, described hereafter as stone dust, was even more effective to explode hydrogen-air mixtures than drops of water. The stone dust used for the experiments was obtained from Messrs. Morgan Crucible Company, and consisted mainly of finely-ground alumina. The material is used in the manufacture of crucibles and other refractories. The experiments are part of a series made in an endeavour to determine the cause of detonation in engines, but the ignition of gaseous combustible mixtures by stone dust is of special interest, because the material is used in mines as a diluent to reduce the inflammability of coal dust.

Experimental Arrangements.

The stone dust was dropped into a stream of hydrogen-air mixture rising in a steel combustion tube held vertically in an electric furnace. The apparatus was arranged as for the experiments on the explosion of gaseous mixtures by drops of water. The method of dropping the stone dust into the mixture is illustrated by Fig. 1. The glass tube, shaped as shown, will retain

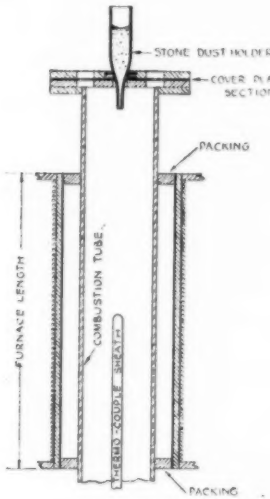


Fig. 1.

ARRANGEMENT FOR DROPPING STONE DUST INTO HEATED GASEOUS MIXTURE.

a charge of the dust, but a light blow with a pencil leads to the discharge of a small quantity from the nozzle. The methods of measuring rates of gas flow and the temperature of the gaseous mixture were as described earlier. The surface of the steel tube was prepared for the experiments by allowing it to become oxidised while exposed to a hydrogen-air mixture containing hydrogen in the concentration to be used for a particular experiment. After a time of exposure varying with the hydrogen concentration, equilibrium conditions are reached and steam formation on the surface then proceeds at a constant rate. The central stream of gas, as it rises in the tube, is depleted of electrolytic gas to maintain the surface action. The inflammabilities of the layer of gas adjacent to the surface and of the central stream of gas become

constant for any particular rate of mixture flow, and the corresponding ignition temperatures have repeatable single values.

Experimental Results.

A hydrogen concentration of 50 per cent. in a mixture with air was selected for the first experiments because when that mixture is passed through the steel combustion tube at a relatively high rate and in equilibrium conditions, an explosion can be obtained by raising the temperature of the tube and a similar effect obtained, but at a substantially lower temperature, by injecting water as nuclear drops. The experiments show that the temperature of

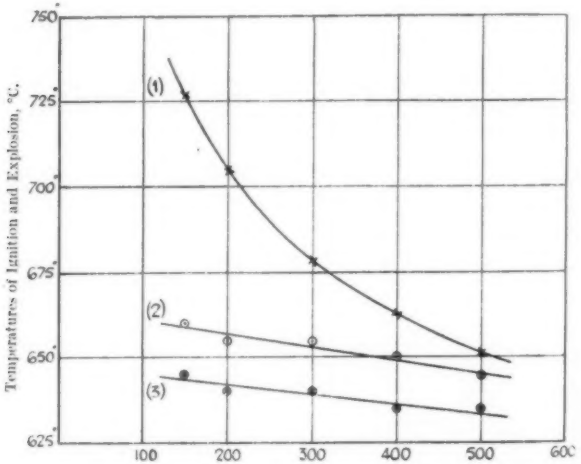


Fig. 2.

Graph (1). Ignition by heating.
Graph (2). Ignition by nuclear drops of water.
Graph (3). Ignition by stone dust.

ignition and explosion by stone dust is still lower. Explosion temperatures corresponding with the three methods of igniting the gaseous mixture are given graphically by Fig. 2, for rates of mixture flow increasing from 150 to 500 c.c. per minute. It will be seen by reference to the figure that at the lowest rate of flow the temperature of explosion by drops of water is about 65° less than that observed when explosion is obtained by heating the tube, and that the difference diminishes as the rate of mixture flow

is increased. The temperature of ignition by stone dust is, however, approximately 15° less than the nuclear drop ignition temperature at any rate of mixture flow.

A second set of experiments was made with a hydrogen concentration of 60 per cent. in the mixture with air. Such a mixture cannot be ignited by heating the combustion tube, Part I., but the effect follows the injection of water or stone dust. The corre-

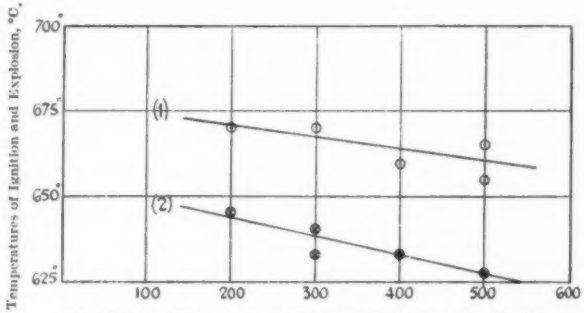


FIG. 3.

GRAPH (1). IGNITION BY NUCLEAR DROPS OF WATER.
GRAPH (2). IGNITION BY STONE DUST.

sponding temperatures of ignition and explosion are given graphically by Fig. 3. It will be seen by reference to the figure that the stone dust ignition temperatures are about 25° below the ignition temperatures observed on the injection of water. The irregularity of the ignition temperatures is attributed to fouling of the surface of the combustion tube by the stone dust blown on to it by the explosions and the consequent alteration of the activity of the surface oxide.

DISCUSSION OF THE EXPERIMENTAL RESULTS.

The experiments support the view that the ignition of heated gaseous combustible mixtures by finely divided particles is not dependent on any change in the nature of the particles themselves. The effect of the particles must be due, then, to a surface action which is independent of their nature. It is well known that drops of water and dust particles become electrified in a stream of gas, but further experiments are required to relate the igniting effect of the particles to the degree and nature of the electrification.

Part IV.—The Explosion by Nuclear Drops of Water of Ethylene-Air Mixtures Passing Through a Nickel-Steel Combustion Tube.

By R. O. King, M.A.Sc. (McGill), and George Mole, B.Sc., A.R.C.S., D.I.C.

Introduction.

The self-ignition and nuclear drop ignition temperatures of hydrogen-air mixtures heated while passing through a chromium-nickel-steel tube, and given in Part I., were observed following relatively rapid changes of hydrogen concentration, the rate of mixture flow being maintained constant. The oxidising and reducing actions proceeding on the surface of the tube were seldom in equilibrium with the hydrogen concentration and the rate of abstraction of electrolytic gas from the mixture varied accordingly. The degree of inflammability of the gaseous mixture in the tube was therefore not always the same for a particular hydrogen concentration and rate of mixture flow, and a corresponding single value for either the self or nuclear drop ignition temperature was not obtained.

The self-ignition and nuclear drop ignition temperatures for ethylene-air mixtures have been determined in conditions approaching equilibrium. Thus, a particular concentration of ethylene was maintained until the corresponding equilibrium oxide was formed and the self and nuclear drop ignition temperatures were then observed for various rates of mixture flow. Ignition and explosion temperatures determined in this way for various ethylene concentrations and rates of mixture supply were found to be repeatable within narrow limits.

Experimental Method.

The $1\frac{1}{4}$-in. internal diameter vertical combustion tube in an electric furnace, the arrangements for injecting water as nuclear drops and for measuring temperature and rates of mixture flow were as described in Part I. A 3 per cent. nickel steel combustion tube was used in the expectation that the oxidation changes required to attain equilibrium with the ethylene concentration in the mixture would occur more rapidly than if the tube were of chromium nickel steel. The experiments were begun by passing the ethylene-air mixture in combining proportions, 6·25 per cent. ethylene concentration, through a clean tube at the rate of 100 c.c. per minute. The formation of the equilibrium oxide proceeded slowly, but repeatable values were obtained eventually for the self and nuclear drop ignition temperatures. The tube surface within the length of the furnace had then become coated with a

thin layer of deep blue oxide over the middle or hottest part, and thin layers of dark brown oxide appeared on the cooler end portions. This oxide distribution appeared to remain unchanged while ignition temperatures were observed with ethylene concentrations varying from 4 per cent. to 8 per cent. When, however, the concentration was increased to 10 per cent., a change appeared in the character of the surface oxides. The layers became denser and were composed of alternate red and blue bands having a general resemblance to the bands of oxide obtained when hydrogen-air mixtures were used in a chromium nickel steel tube, see Fig. 6 of Part I. The surface finally attained changed little in appearance with changes of ethylene concentration within the range 5 per cent. to 10 per cent., or with change in rate of mixture supply from 50 c.c. to 500 c.c. per minute.

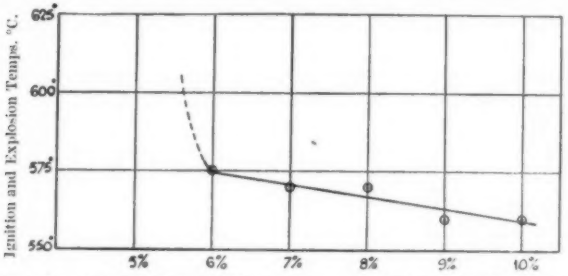
Experimental Results.

The temperatures at which ignition and explosion occurred on heating the combustion tube or on injecting water as nuclear drops were observed for ethylene concentrations varying by whole numbers from 5 per cent. to 10 per cent. and at every con centration for rates of mixture supply varying from 50 c.c. to 500 c.c. per minute. Ethylene was not used in greater concentration than 10 per cent. because the self-ignition then obtained was not explosive and the temperature of the beginning of the effect could not be observed accurately in the conditions of the experiments.

When the rate of mixture supply was less than 100 c.c. per minute, the mixture in any concentration of ethylene could not be ignited on raising the temperature, but ignition and explosion occurred on the injection of water and for rates of mixture supply as small as 50 c.c. per minute. The ignition temperatures thus obtained for ethylene concentrations varying from 6 per cent. to 10 per cent. are given by Fig. 1. Referring to the figure, it will be seen that nuclear drop ignition temperature diminishes uniformly with increase of ethylene concentration, and that it could not be obtained for a concentration of less than 6 per cent. if the rate of mixture supply were 50 c.c. per minute only.

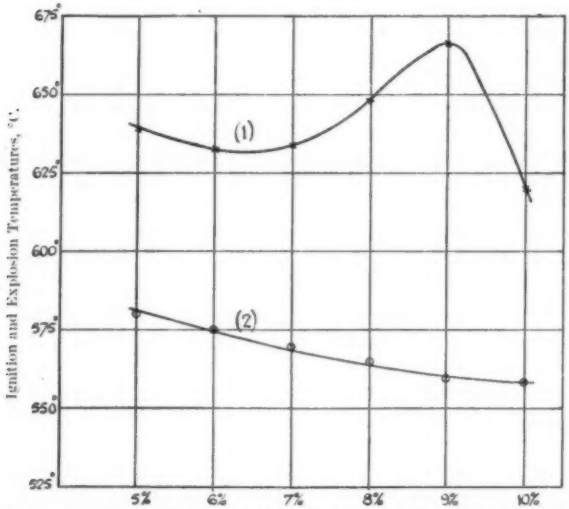
When the rate of mixture supply was increased to 100 c.c. per minute, ignition occurred either on raising the temperature or, at a lower temperature, on the injection of water. The corresponding ignition temperatures are given graphically by Fig. 2, and it will be seen that for 9 per cent. ethylene concentration the nuclear drop ignition temperature is 100°, approximately lower than the self-ignition temperature.

The self-ignition temperature falls as the rate of mixture supply is increased, and tends to become of the same value as the nuclear drop ignition temperature. The collected experimental results



Ethylene Concentration in Mixture with Air. 50 c.c. per minute. Rate of Mixture Supply.

FIG. 1.
NUCLEAR DROP IGNITION.



Ethylene Concentration in Mixture with Air. 100 c.c. per minute. Rate of Mixture Supply.

FIG. 2.
GRAPH (1). SELF IGNITION.
GRAPH (2). NUCLEAR DROP IGNITION.

for rates of mixture supply of 100, 120, 200, 300, 400 and 500 c.c. per minute are given graphically by Fig. 3. Self-ignition temperatures are shown by the dotted lines of the figure. The nuclear

drop ignition temperatures for all of the ethylene concentrations and rates of mixture supply fall within the narrow zone bounded by the unbroken lines of the figure.

Discussion of the Experimental Results.

It is well known that the beginning of the oxidation in the gaseous phase of ethylene and other gases containing carbon in the molecule, is indicated by the formation of fog. The fog particles are oxidation nuclei and are visible in a beam of light passing through the heated gaseous mixture. The graphs of

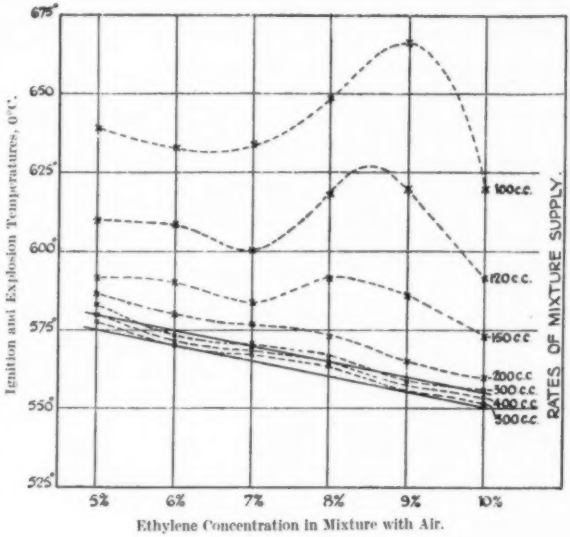


Fig. 3.

VARIATION OF IGNITION TEMPERATURES WITH ETHYLENE CONCENTRATION AND RATE OF MIXTURE SUPPLY.

Dotted Lines—Self-ignition Temperatures. Nuclear Drop Ignition Temperatures fall within the unbroken lines.

Fig. 3 are consistent with the view that the oxidation nuclei act as centres of self ignition, explosion occurring when a sufficient concentration of the nuclei is attained. Ignition and explosion can be obtained in the absence of a high concentration of oxidation nuclei by nuclear drops of water acting as centres of ignition. The experimental results may now be reviewed in the light of the nuclear hypothesis.

When the gaseous mixture is supplied at so low a rate as 50 c.c. per minute, surface action on the oxidised steel tube removes so much of the combining proportions mixture in the gaseous stream that the possible concentration of oxidation nuclei in the remainder is insufficient to lead to ignition and explosion. The mixture rising in the combustion tube is, however, still sufficiently inflammable to be exploded if centres of ignition are provided by injecting water as nuclear drops, as shown by the experimental results, Fig. 1. A similar effect can be obtained by dropping stone dust into the mixture.

When the rate of mixture supply is increased to 100 c.c. per minute, Figs. 2 and 3, sufficient combining proportions mixture remains in the gaseous stream to provide oxidation nuclei in the concentration necessary for ignition and explosion. Inflammability increases as the quantity of combining proportions mixture in the gas supplied reaches a maximum, then decreases as the quantity mentioned diminishes as the concentration of ethylene exceeds that required for combining proportions. The second and later increase of inflammability is attributed to the profusion of oxidation nuclei formed when the mixture supplied contains ethylene greatly in excess of combining proportions.

The rate of mixture supply being increased to relatively high values, the quantity of combining proportions mixture consumed by surface action becomes a small part of the total available and the temperature of self ignition tends to be dependent entirely on the concentration of oxidation nuclei, which increases as the concentration of ethylene in the mixture is increased. The effect is shown clearly by the experimental results for rates of mixture supply of 200 c.c. to 500 c.c. per minute, Fig. 3.

SEVENTH MEETING OF POLISH OILMEN

By Stanislaw Pilat, Ph.D. (Member).

The Seventh Meeting of Polish Oilmen was held at Boryslaw, Poland, from December 15th to 17th, 1933, when twenty-seven papers on subjects relating to Petroleum Engineering, Petroleum Economics and Refinery Engineering were read and discussed.

The papers of more than local interest were the following :—

Programme of Prospecting Drilling in Poland. K. Tolwinski.—This paper constitutes a general discussion of the programme of drilling for oil in the Carpathian and Sub-Carpathian provinces of Poland. The following petroliferous provinces are taken in consideration :

The Area of Marginal Zone.—The starting point for this zone is Boryslaw, the most prolific oilfield of Poland. The geological unity of Boryslaw oilfield occurs in the front of the orographically exposed Carpathian ridge at a distance between the Pokucie Carpathes and Dobromil Carpathes. In addition to Boryslaw, this structural unity is productive also in the oilfields of Bitkow, Rypne and Nahujowice, while the south-east part situated between Rypne and Chyrow is insufficiently tested by deep drillings. On the basis of geological consideration these two parts of Boryslaw unity represent important possibilities as regards prospecting for oil.

The marginal zone has also other types of oil structures, such as Schodnica, Urycz, Grabowka, Weglówka, oilfields bound to structures occurring in slices (skiby) complexes. This area covers a surface over 6000 square kilometres. Many favourable structures promising for oil prospecting are as yet insufficiently tested with deep drillings.

The Median Zone.—This area occupies approximately 5000 square kilometres. In the western part the producing oilfields comprise the well-known anticlines of Potok, Bóbrka-Rogi, Iwonicz, Lipinki. Many other structures are to be tested. The productive horizons are dipping in a south-east direction, covered by younger formation. No test wells had been drilled to ascertain the oil possibilities. The eastern part of the Median zone, situated near to Bukowina frontier, is characterised by many oil seepages recently rediscovered. This area represents many good possibilities for prospecting work.

THE MAGURA OVERTHRUST ZONE, produced in the last century some oil chiefly extracted from hand-dug shafts. The oilfields of Magura zone are not very prolific but have the advantage of small depths and long-lived production. The old mines are situated on a great area, over 100 kilometres in length. For many years no prospecting work has been done here. The exploration programme should take into consideration the production possibilities of the Magura zone, too.

THE SUB-CARPATHIAN PROVINCE is situated between the Carpathes and Podolian plateau, and embraces an area of about 20,000 square kilometres. The prevailing formation is the Miocene, over 2000 metres in thickness, composed chiefly of shallow deposits and provided with oil and gas seepages. Until now only the gas field of Daszawa had been discovered in this area. Different zones are recognised in the Sub-Carpathian province, the main feature of the marginal zone being characterised by the predominance of saliferous formation. The drilling at Starunia and Dzwiniacz has proved that below the saliferous formation occurs the Carpathian flysh. The commercial value of that zone will be tested in the near future by a well recently located on the Truskawiec structure.

The Median zone, situated to the north, is characterised by the occurrence of folds of diapir type, similar to the Rumania diapir structures. The occurrence of salt plugs is known in many localities of that area and should be taken in consideration as representing great possibilities for prospecting drilling. Finally, the most northly situated zone of the Sub-Carpathian province, with a producing gas field in Daszawa, represents an important prospecting value for both gas and oil.

Investigation on the Increasing the Ultimate Recovery of Boryslaw Oilfield. BUREAU OF ASSOCIATION OF POLISH PETROLEUM ENGINEERS.—Poland's crude oil production from 1886 to the end of 1932 totalled 29,760,000 tons, of which over 77 per cent. (23,134,488 tons) came from the Boryslaw oilfield. In recent years the production of this oilfield has decreased about 10 per cent. yearly. Swabbing, which is still in use as an exploration method, should be replaced by pumping and the ultimate output of the field could be increased by repressuring. Evaluating the possibility of production by this method, the ultimate recovery could be increased by 11,500,000 tons of oil. The Bureau proposes to carry out a detailed investigation on the possibility of applying the repressuring method to the Boryslaw oilfield.

Statistics of Poland's Petroleum Production with Special Reference to Boryslaw Oilfield. Z. BIELSKI.—This paper deals with the production figures and operating costs prevailing in the Drohobycz, Stanislawów, and Jaslo districts. About 70 per cent. of the total Polish production came from the Boryslaw oilfield. The actual operating wells are divided into three groups, in order of their average daily yield. More than 70 per cent. of the Boryslaw wells are producing less than 30 tons of crude daily. To make the exploitation beneficial, swabbing should be completely abandoned and improved pumping methods introduced. The use of Schweiger (Hughes) installation is recommended.

Deep-Well Pumping in Boryslaw Oilfield. W. SKOCZYNSKI.—This paper covers a brief discussion of the advantages, both economical and financial, by using deep-well pumps in Boryslaw oilfield.

Production Curves of Polish Oilfields. O. V. WYSZYNSKI.—The American experiences in constructing production decline curves are adopted for the first time on a large scale for the Polish oilfields. Production curves for hundreds of individual wells and average group curves have been constructed and an endeavour made to find a mathematical expression for them. Both mathematical and graphic construction for average curves were used, and graphs on logarithmic and semi-logarithmic paper drawn.

In spite of the very changing conditions of the Flysh reservoirs, satisfactory results are obtained. Tables showing the co-ordinates for average production curves for various oilfields are given.

The relation between the reservoir characteristics and the type of production curve are analysed, and may be briefly stated as follows :—

(1) The production decline curve is of hyperbolic type, expressed by an equation $x\,y^n=k$, if the reservoir is of open type. The expellant force, both the gas pressure and the dimishing hydrostatic head, and the producing sandstone is porous. Most Polish Carpathian oilfields follow that type of production curve.

(2) The production curve is of exponential type, expressed by an equation $Y=a\,e^{-Kx}$ if the reservoir is of closed type, encroaching water does not exist, the reservoir rocks are of high and uniform porosity and the only expelling force is the pressure of gas dissolved in the oil. Examples for that case are given from Bitków, Wankowa and Równe oilfields.

(3) The production decline is a lineal function under following reservoir conditions : the reservoir is of open type, the diminishing

hydrostatic pressure is the principal expellant, and the reservoir rocks are porous. Curves from Potok anticline were selected for illustration of that case.

(4) The production curve follows in the first stage a hyperbolic equation while in the second one the production is constant. If the reservoir is of open type, the expellant is both the gas pressure and the constant hydrostatic head. Examples from Wankowa and Brelików oilfields are given.

(5) The production decline is composed by several lineal functions if the reservoir conditions, with exception of porosity, are the same as described in the case (3).

This case is illustrated with an average curve for the third horizon of Równe anticline.

Improvements in Production Engineering in the Jaslo Oil District. J. CZASTKA.—Modern production methods were introduced during the last year in the Jaslo oil district. A bean placed at the bottom or on the top of tubing in flowing wells of the Humniska oilfield is successfully used. Slow speed pumps, air-lift displacement pumps, and the gas-lift method, after a device patented by W. Lodzinski and Jat Miller, are operating in the Grabownica oilfield.

Results of repressuring method installed in Lipinki and Toroszka are described.

Contribution to Repressuring Studies. Z. WILK.—A detailed description of the repressuring installation used in the Schodnica oilfield is given.

The behaviour of the injection wells, the reaction in the surrounded wells, the volume of the injected air, as well as the pressure, the increased oil recovery and the analysis of oil and gas are discussed.

Results of Repressuring Method with Compressed Air Adapted in the Schodnica-Urycz Anticline. H. GORKA.—Reference to the literature on the subject are given. The following problems are discussed: the flow of air and gas through porous media, the solubility of natural gas in crude oil, the flow of saturated oil at back pressure above saturated pressures.

The geological structure of Schodnica-Urycz anticline is described. It is a gentle anticlinal fold extending in N.W.–S.E. direction. Two transversal faults are known in the central part of the anticline. The Jamma sandstone is the producing horizon of both the Schodnica and Urycz oilfields. The texture of the sandstone is coarse or medium grained and of high porosity. The

production area, 7 kilometres in length, embraces a surface of about 240 hectare. The depth of producing wells, ranges from 300 to 500 metres. Salt water occurs in the southern part of the anticline. Schodnica and Urycz fields have been producing since 1881 year, the total output until the end of 1932 being 2,468,000 tons of crude oil. The average yield per well is 4000 tons for Schodnica and 3500 tons for Urycz.

The repressuring method was first adopted in May, 1931, by the Gazy Ziemne Co. The favourable results obtained then encouraged the other companies operating the Schodnica-Urycz anticline to introduce the method for their properties.

A detailed description of the installation and the behaviour and respective reaction of the wells due to repressuring are given.

The total amount of injected air is 8,843,294 cubic metres.

A total increase of 13,220 tons of crude oil has been obtained by the use of the repressuring method.

Analyses of crude oil taken before and after the injection are given. No changes in chemical composition are noticed.

Principles and Results of the Seismic Reflection. Methods in the United States. Z. MITERA.—A brief review of principles underlying seismic methods emphasising those of reflection methods. Some results of application of these methods are shown and the possibilities of applying them in Poland are discussed. The economical value of these methods for the increase of oil production in the United States are presented in the form of graphs.

Porosity and Permeability of Oil-Bearing Rocks with Reference to Field Problems. A. DRAHT.—A review of American papers dealing with the porosity and permeability problems.

Technical Petroleum Development in Russia.—Z. SZWABOWICZ.—Technical improvements in drilling installations, seen during a visit to Russia, in the Grozneft and Azneft oil districts, are described. Special attention is drawn to the " Kapeluszników " turbo-drilling installation.

Production and Organisation in the Russian Oil Industry. J. WOJNAR.—The author describes the organisation scheme prevailing in the Russian oil industry, the division of the producing oilfields into sections and districts, as well as the organisation of the Petroleum Institutes at Baku and Grozny.

One of the most outstanding accomplishments of Russia's programme are the improvements in production and drilling methods, specially in the air and gas lift and in the turbo-drill.

The total yearly recovery has decreased during the two last years of "Piatiletka." In the author's opinion the Russian oil will not be a dangerous competitor to other producing nations in the near future.

Technical Progress in Petroleum Development in the U.S.A. W. KLIMKIEWICZ.—A summary of the last progress in the technical development in the U.S.A. is given. The author recognises that the rapid progress of petroleum engineering realised in the U.S.A. during past years has an important influence for the development of the technique in Poland's oil industry. Many engineering efficiencies long practiced in the U.S.A. are accepted by the Polish engineer and every branch of development and production work is now undergoing a study in order to make it suitable for local conditions.

Utilisation of the Refinery By-Products. J. SEREDA.—It is pointed out that, contrary to common opinion, the acid sludge resulting from treating lubricating oils with sulphuric acid contains between 30–50 per cent. of unpurified sulphonic acids. These acids can easily be recovered from the sludge and separated into different classes following the A. Pat. 1,933,070 or the Brit. Pat. 343,530. The author described a plant based on those patents and gave some information as to the application of these sulphonic acids and their salts for wood preserving, tanning, emulsifying and for some pharmaceutical preparations of importance. At the end of his lecture he described briefly a new industrial method (Polish Pat. appl. 41,915) of separation of oil-soluble sulphonic acids from neutral oils and naphthenic acids.

Some Physico-Chemical Characteristics of Sulphonic Acids from Petroleum Products. MISS E. NEYMAN.—Practical applications of those by-products of lubricating oil treatment necessitated an investigation of their physico-chemical properties, such as surface tension and interfacial tension, the solubility in water of some practically insoluble salts, adsorbtivity and electrical conductance. Like most colloids of the hydrophile class, various salts of sulphonic acids considerably reduce the interfacial tension and act therefore as very efficient emulsifiers. A commercial plant which uses some of the sodium salts for emulsifying gasoline with water, giving a water-soluble emulsion, has been mentioned.

Determinations of electrical conductance have shown that these sulphonic acids range among the fairly strong organic acids highly dissociated, which form completely neutral alkali salts.

Fractionation of Low Boiling Hydrocarbons. K. KLING and B. WIECLAWEK.—The authors describe first an apparatus adapted to the laboratory production of low-boiling hydrocarbons in quantities of several litres. They mention an apparatus for analytical determination of the same substances and present some data of their investigations. Both apparatus consist of a fractionation column, the outside walls of which are formed by a Dewal flask suitably adapted. The fractionation takes place at normar pressure.

The Pyrolysis of Hydrocarbons. A. SZAYNA.—The paraffinic class is less resistant towards heat than cyclic saturated hydrocarbons (naphthenes), aromatic hydrocarbons being the most stable. Even within that class differences exist. The author gives an example of aromatic hydrocarbons ranging from the most stable according to their decreasing thermal resistancy ; benzene, toluene, diphenyl, naphthalene, anthracene, phenyl-octadecane and the paraffinic octadecane at the end.

The author suggests that higher paraffinic hydrocarbons, under the conditions of high-pressure hydrogenation, undergo cleavage of molecules of smaller size than the starting hydrocarbons. For example, normal octadecane splits into homologs of all sizes from C_{17} down to gas molecules, the amount of each fraction increasing inversely to the molecular weight. From one mole octadecane, which has been cracked, are formed more than two moles of hydrocarbon products, in spite of the fact that a part of the starting material withstands the cracking.

The author suggests that, under the above conditions, molecules of octadecane split once, each at a different linkage and the products of this "primary cleavage" undergo further decomposition. The rate of the decomposition increases with the size of molecules. No privileged points of breaking were detected, with the exception of the terminal linkage (methyl group at the end of the chain), which is probably more stable.

The Use of Asphalts Manufactured from Paraffinous Petroleum as Road Material. F. LIMBACH.—The author discusses the results of his practical experience in road making with petroleum asphalts containing paraffin wax, and comes to the conclusion that, with regard to the Polish climate and local conditions, asphalt-macadam ought to be the best for the roads. He points out the filling material must be such as to decrease only slightly the plasticity of the asphalt at low temperatures, but to raise its softening point (R. and B.) to above 80° C.

The Behaviour of Lubricating Oils in an Automotible Motor. R. OREL.—The author presents the results of his practical tests with different oils and different motor cars and investigates the relationship between mileage and oil dilution by gasoline. There is considerable difficulty in determining the point at which the oil becomes useless, as the dilution by gasoline is counteracted by sludging and metallic dust. Numerous experimental data were given with reference to oil dilution and its relation to the original viscosity of the oil sludge and coke formation.

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